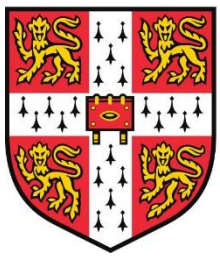
Life in Medieval Cambridge: an isotopic analysis of diet and mobility



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THIS THESIS IS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Declaration

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. I further state that no substantial part of my thesis has already been submitted, or, is being concurrently submitted for any such degree, 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 for the relevant Degree Committee.

Abstract

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Alice Rose

Cambridge was a well-established town and an important trade centre in the High and Late Medieval period (11th-16th century). Historical accounts and archaeological evidence indicate that the Late Medieval period was a tumultuous chapter in English history, with episodes of war, climate change, famine and plague. It is argued that the social and economic changes, particularly those associated with the Black Death of 1348-50, would have significantly affected food production and procurement in England and that dramatic population reduction may have resulted in changes in population replacement and diversity. However, it is not fully understood to what extent events in the Late Medieval period affected towns like Cambridge, and whether they were experienced universally across the local population.

This thesis utilises contextualised isotope analysis of human and faunal skeletal remains from cemetery sites excavated from Cambridge and its hinterlands to investigate what life was like for the population living in the High and Late Medieval period. Isotope sampling focussed on High and Late Medieval skeletal remains, but to evaluate the scale of change across the longue durée, skeletal remains dating from the Neolithic to the Post-Medieval period were also sampled. A multi-tissue (bone, dentine, enamel) multi-isotope ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$) approach was used to understand how diet and mobility varied at an intra- and inter-individual and population scale. Collagen from 246 faunal bones, 227 human tooth roots and 314 human ribs was analysed for $\delta^{13}C$ and $\delta^{15}N$, carbonate from 295 tooth crowns was analysed for $\delta^{18}O$ and $\delta^{13}C$, and 170 tooth enamel samples were analysed for $^{87}Sr/^{86}Sr$. Successful results were combined with previously generated data from the area, totalling 252 faunal isotope results and 1174 human isotope results.

The results of the isotope analysis have allowed for the characterisation of diet across multiple sites, indicating variation based on social status, religious beliefs and locality. Isotope analysis has identified a small number of individuals who were unlikely to have spent their childhood in Cambridge and may have migrated into the town. Potential localised, short-distance migration in women has also been identified. Most importantly, this thesis concludes that the data does not show conclusive temporal changes in the High and Later Medieval periods which could be linked to events in the 14th century. Some general temporal change in diet may be present, but this is likely to be linked to the increasing popularity of marine fish consumption following the 'fish event horizon'.

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Abbreviations

aDNA	Ancient Deoxyribonucleic Acid (genetics)
ATP	After the Plague (project name)
DDC	Detect Deviating Cells (statistical package)
EDJ	Enamel-dentine junction (dental anatomy)
IQR	Interquartile range (statistics)
LEH	Linear enamel hypoplasia (dental pathology)
M2	Second molar (dental anatomy)
PM2	Second premolar (dental anatomy)
PSN	Project Skeleton Number (unique identifier for **ATP** project)

Glossary

Term	**Type**	**Meaning**
Aetiology	Medicine	Cause of a disease
Alien	Medieval legal term	People who owed no direct allegiance to the sovereign power of the country
Bagplot	Graphical data representation	Similar to a **boxplot** but in two dimensions. Displays the depth median of the data, the 50% of data closest to the depth median (analogous to **interquartile range**) and outliers.
Bioapatite	Biochemistry	Inorganic structural calcium phosphate component of bone, **dentine** and tooth **enamel**
Boxplot	Graphical data representation	Displays the median of the data, the maximum and minimum, the first and third quartiles of the data, the **interquartile range**, and outliers.
Collagen	Biochemistry	Organic structural protein component in bone and **dentine**
Corrody/ Corrodian	History	A corrody was a provision of services, mostly food and care, by a religious institution essentially like a pension. A corrodian was generally an older lay person who paid to be accommodated in a religious institution, like a care home.
Dentine	Dental anatomy	Tissue that forms most of a human tooth, including roots
Demesne	History	Manorial land under feudal system
Diadromous	Biology/ecology	Fish which move between both freshwater and saltwater environments
Enamel	Dental anatomy	Hard tissue that forms the crown of a human tooth
Interquartile Range	Statistical	Middle 50% of data, when data is divided into quartiles

Isotope	Chemistry	Atom of an element with the same number of protons but different number of neutrons, affecting its atomic mass.
Isotope Enrichment	Chemistry	Where the relative abundance of one **isotope** of an element increases while the abundance of another isotope decreases
Kernel Density Estimation	Statistical	Non-parametric estimation of probability density
Murrain	History	Generalised term for mass disease of livestock, most often cattle or sheep
Pathogen	Medicine	Organism that can cause disease
Raincloud plot	Graphical data representation	Displays one-dimensional data. Consists primarily of **kernel density** estimations plot(s), with **boxplots** and **scatter plots** where appropriate. Displays information about data distribution and density, as well as individual data points and added information provided by the **boxplot**(s).
Scatter plot	Graphical data representation	Typically two-dimensional, although plots can be three-dimensional. Displays relationship between two (or three) variables.
Violinplot	Graphical data representation	Consists of a **boxplot** and a mirrored **kernel density** plot. Displays the same information as a boxplot, but with added information about data distribution and density.



1. Introduction

Cambridge was a well-established town in the High and Late Medieval period (11th-16th century). It was an important trade centre in the East of England and a multitude of religious and university establishments were founded during this time. As a result, Cambridge would have been home to a wide variety of people and may have had great social stratification, much like today. While thanks to the enduring legacy of the University, it sometimes feels like not much has changed in Cambridge between the Medieval period and now, there are many aspects about life in Medieval Cambridge and how this differed between various social groups about which little is known. The Late Medieval period was a particularly tumultuous chapter in English history, with episodes of war, climate change, famine and plague. It is argued that the social and economic changes, particularly those associated with the Black Death of 1348-50, would have greatly affected food production and procurement in England and that dramatic population reduction may have resulted in changes in population replacement and diversity. However, it is not fully understood to what extent events in the Late Medieval period affected Cambridge, and whether they were experienced universally across the town.

Social and economic historians have used sources such as clerical records, land registers, food assizes and contemporary narrative accounts to quantify and characterise life in the Medieval period, indicating significant changes in social structure, economy and general quality of life. However, available documentation for Cambridge is sparser and evidence for the impact of the Black Death is often indirect. Historical documents tend to be intermittent, inconsistent and focused on the concerns of landowners, scholars and the clergy. They do provide insight into Medieval life, but they are often biased towards certain social strata and do not allow for a full understanding of the lived experiences of 'ordinary' people. Similarly, the wide variety of

archaeological evidence available from excavations in and around Cambridge can be used to estimate aspects of the lived experience such as standards of living, settlement size and foods utilised but all of these forms only provide information about the potential collective living environment, rather than individual circumstances. The actual, physical skeletal remains of the people who lived through this period can bridge this gap, revealing important information regarding personal experience. Various analyses of skeletal material can provide a wide array of information about demography, pathologies endured, dental health, nutritional stress, and genetic history but presently, only isotope analysis can provide direct evidence of individual diet and mobility, two aspects which are likely to have changed greatly during the High and Late Medieval period in Cambridge.

Based on principles established by DeNiro and Epstein (1978, 1981), direct evidence of the diet that an individual consumed during life can be reconstructed through analysis of isotopes of carbon (C) and nitrogen (N) in skeletal tissues. The $\delta^{13}C$ values largely reflect the contributions of plants of different photosynthetic pathways (C_3 or C_4) to the diet, whereas the $\delta^{15}N$ values reflect the animal proteins consumed. Marine fish consumption can also be detected as marine protein is generally distinctly enriched in ^{13}C and ^{15}N (Schoeninger and DeNiro 1984). Following slightly different principles (Longinelli 1984, Luz, Kolodny, and Horowitz 1984, Ericson 1985), isotopes of oxygen (O) and strontium (Sr) in tooth enamel can be used to estimate the climatic and geological isotopic signature of where an individual spent their childhood, and crucially, whether this appears to match the bioavailable isotopic signature of where they were buried. Mismatches can potentially reveal migration. Skeletal tissues develop and regenerate at different rates, so combining multiple isotope analyses of multiple skeletal tissues representing childhood development (tooth enamel and dentine collagen) and years before death (bone collagen) can therefore be a powerful tool in reconstructing information about archaeological individuals.

Isotope analysis has been applied to High and Late Medieval skeletal collections in England but most large scale studies have largely been confined to Northern England, particularly Yorkshire (Müldner and Richards 2005, 2007a, 2007b, Bownes *et al.* 2018). Apart from a comprehensive isotope study investigating skeletons spanning a period of 1500 years in York (Müldner and

Richards 2007b), no other large-scale isotope study published to date has intensively investigated changes throughout the Medieval period across a single town or locality.

This thesis, therefore, takes a 'whole-town' approach. It utilises large scale, multi-tissue (bone, dentine, enamel), multi-isotope ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $^{87}Sr/^{86}Sr$) analysis of skeletal remains from a variety of cemetery populations from Cambridge and its hinterlands to understand how diet and mobility varied at an intra- and inter-individual and population scale, in order to ultimately investigate the lived experience of people from a single Medieval town in the East of England. There are a large number of suitable skeletal remains that have been excavated from the local area which have been subject to very little previous osteological or isotope analysis, making them prime material for new research. To pursue a 'whole-town' approach, the cemetery populations chosen for analysis in this thesis represent a cross-section of urban and rural society, from 'normal' parish populations to specialist hospital and friary institutions. The human skeletal remains sampled for isotope analysis are primarily dated to the High and Late Medieval periods, so that diet and mobility during this period can be investigated in high resolution, paying particular attention to changes occurring during and after the 14th century. Samples were also taken from populations spanning from the Neolithic (c.4000-2200 BC) to the Post-Medieval (AD 1540-1901) period to place the High and Late Medieval data in a broader chronological context. To characterise the isotopic 'baseline' for Cambridge, and therefore make the chronological comparisons of human $\delta^{13}C$ and $\delta^{15}N$ values more robust, terrestrial and aquatic fauna dating from the Iron Age (c.800 BC-AD 43) to the Post-Medieval period were also sampled for $\delta^{13}C$ and $\delta^{15}N$ analysis. In total, collagen from 246 faunal bones, 227 human tooth roots and 314 human ribs was analysed for $\delta^{13}C$ and $\delta^{15}N$, carbonate from 295 tooth crowns was analysed for $\delta^{18}O$ and $\delta^{13}C$, and 170 tooth enamel samples were analysed for $^{87}Sr/^{86}Sr$ as part of this thesis. Successful results were combined with previously published and unpublished isotope data from the area, totalling 252 faunal isotope results and 1174 human isotope results which are investigated through chronological, demographic and social criterion. Combining this direct evidence from isotope analysis with the osteological, archaeological and historical documentary data provides extensive new information about life in Medieval Cambridge from the intra- and inter-individual to the population level, allowing for high-resolution characterisation of the impact of events in the Late Medieval period in the context of

the longue durée (taken here to broadly mean deeper chronological time spanning before and after the High/Late Medieval period).

1.1 After the Plague: Health and History in Medieval Cambridge

This PhD was conducted as part of the 'After the Plague: Health and History in Medieval Cambridge' project, led by Professor John Robb (2016-21, Wellcome Trust Award 2000368/Z/15/Z). 'After the Plague' is a multi-disciplinary bioarchaeological project formed of bioarchaeologists, bioanthropologists, geneticists, archaeologists and historians which aims to bring together osteological, palaeopathological, metrical, genetic and isotope data, along with historical documentation and archaeological evidence, in order to answer questions relating to the social and biological consequences of the Black Death in Cambridge The main research questions at the start of the project were: How did living standards and conditions change after the Black Death of 1348-50, in particular, were there changes in patterns of activity, diet and geographical mobility? What were the biological consequences of the Black Death, particularly concerning biological well-being, disease patterns and genomic change? And, when put into a long-term context, are the changes surrounding the Black Death minor short-term fluctuations or substantial, even transformative historical changes? (Robb 2016). The project considers these questions on a population scale and an individual scale, particularly through osteobiography (Robb *et al.* 2019). This thesis is its own contained body of research with its own intrinsic aims focussing on diet and mobility, but due to the nature of being part of a larger project, the aims of this thesis complement those of the After the Plague project and the materials employed were negotiated in collaboration with the larger research group. The project will culminate in a monograph: 'Health and History in Medieval Cambridge' (Robb n.d.). The monograph is referenced throughout this thesis as it is the best or only source for much of the information about Cambridge, but it is currently not yet published.

1.2 Research Questions and Aims

The overall aim of this thesis is to utilise contextualised isotope analysis to characterise diet and mobility in High and Late Medieval Cambridge to understand how this varied at an intra- and

inter-individual and population scale, and see whether this changed through time, particularly after the mid-14th century.

In order to address this broad aim regarding diet and mobility, the specific research questions to be addressed with the Cambridgeshire skeletal material are:

- To what extent can the isotope values for relevant foodstuffs be characterised for Cambridge to aid interpretations of human diet? Particularly, what was the faunal isotopic baseline and how does this change across the longue durée?
- To what extent can human diet and protein contributions be characterised using carbon and nitrogen isotope values, e.g. is there evidence of marine fish consumption?
- Are there meaningful differences between carbon and nitrogen isotope values in different skeletal tissues? Can these inform us of differences between childhood and adulthood diet?
- How many individuals are outliers, particularly in their oxygen and strontium isotope values, which might indicate how many are of 'non-local' origin?
- Are there meaningful differences in the numbers of individuals who are outliers and/or of 'non-local' origin between sites and social groups?
- Are there meaningful differences in isotope values between sites?
- Are there meaningful differences in isotope values by sex and/or social group?
- Are there meaningful differences in isotope values pre- and post- AD 1350, by Medieval century or in the longue durée?

1.3 Thesis Structure

Chapter 2 provides a brief outline of the history of the development of Cambridge and its character as a Medieval town in order to place the sites investigated in this thesis into context. The chapter then discusses the instrumental events of change in the Late Medieval period and the evidence for how these may have affected Cambridge directly. Most importantly, the chapter discusses the current archaeological, historical and isotopic evidence for diet and mobility in the High and Late Medieval period in England and Cambridge specifically.

Chapter 3 summarises the use of isotope analysis in archaeology. It explains the underlying principles behind each type of isotope analysis utilised in this thesis, highlighting what information each isotope is most suited to provide, as well as the limitations of the techniques. Following this is a discussion of how isotope analysis might be best applied to High/Late Medieval Cambridge and predictions of the data that might be gained.

Justifications of the approach taken, and the methods chosen are given in Chapter 4, along with a gazetteer of the sites and samples chosen for analysis. The methodology applied is then given in Chapter 5, and an overview of the quality and success of the resulting data is provided in Chapter 6.

Chapter 7 presents the High and Late Medieval isotope results, with some discussion of the key trends. Chapter 8 then places the High and Late Medieval data into context with data across the longue durée, spanning from the Neolithic to the Post-Medieval period, to assess the extent of changes in the Late Medieval period in comparison with longer-term changes. Key findings are then discussed in more detail in Chapter 9, which places the isotope results into context with the archaeological and historical information, and comparable isotope studies. Chapter 10 provides final conclusions, summarises to what extent the data has fulfilled the research aims and provides suggestions about future research directions.

Further tables and figures, full results of statistical analyses, gazetteers of comparative sites and laboratory standard operating procedures are provided in the appendices associated with this thesis. The full primary and comparative human and faunal isotope dataset is available on the Cambridge research repository Apollo, which can be accessed at: https://doi.org/10.17863/CAM.71053.

For clarity, as Cambridge was only granted city status in 1951, when referring to Cambridge in the past, it will be referred to as a town. Descriptions of the location of archaeological sites will refer to landmarks in the modern city, as well as other modern settlements, in order to aid the reader. Similarly, when referring to 'Cambridgeshire', this is in reference to the modern county boundary, again with the purpose of aiding the reader in understanding the location of the archaeological sites. Modern Cambridgeshire encompasses a larger area than previous historic county boundaries and boundaries have moved throughout the early periods in Cambridge, therefore modern concepts of 'Cambridgeshire' may not correlate with concepts of the region in the past.

Illustrations of several of the individuals analysed from Medieval Cambridge have been produced by Mark Gridley for the 'After the Plague' project and have been used in this thesis as chapter headings. Permission to reproduce the illustrations by Mark Gridley has been granted by John Robb, Principal Investigator of the 'After the Plague' project.



2. Cambridge in Context

This Chapter provides a brief historical background to High/Late Medieval Cambridge in order to place the research in this thesis into context. As the isotopic techniques employed in this thesis primarily provide information about diet and migration (see Chapter 3 for principles of isotope analysis), the rest of this chapter focusses on discussing historical, archaeological and isotope research in these areas, discussing wider knowledge of diet and mobility in High/Late Medieval England, as well as what evidence is currently available for Cambridge and its environs.

2.1 A Brief History of Cambridge and its Environs

The geography, geology and hydrology of Cambridgeshire have been influential factors throughout its development (Lobel 1975, pp. 1–7). In terms of available soils, Cambridgeshire is characterised by clays and chalkland to the South and peat fens to the North, whose height above sea-level has varied through time (Lee *et al.* 2015). There are three major rivers – the Great Ouse, the River Cam (a tributary of the Great Ouse, previously called the Granta) and the River Nene. These rivers all flow into the Wash, connecting Cambridgeshire with the sea.

Evidence for a Late Iron Age settlement has been found on Castle Hill, Cambridge (Alexander and Pullinger 2000). Excavations suggest this was superseded by a Roman defended *vicus*, taking advantage of the position on the River Cam and several converging roads (Smith and Fulford 2019, pp. 118–121, Evans and Lucas 2020). In the Early Medieval period (5th to 11th centuries), Cambridge was located on a boundary and fluctuated between Saxon Kingdoms until the 9th century. Cambridgeshire was under Danish control ('Danelaw') between c.AD 886-921 and later became part of the Kingdom of Wessex. Despite these changes, Cambridge slowly became a

centre for trade and administration in Cambridgeshire in this period, largely due to its road and waterway connections, allowing access to the Wash (Lobel 1975, pp. 2–5, Cessford and Dickens 2019, pp. 35–43).

During the High/Late Medieval period (11th-16th centuries), Cambridge continued to exploit its advantageous position on the river, linking it to the important Medieval centres of Ely and Lynn, as well as the sea. This allowed it to continue to grow as a centre for trade, and later, education. Cambridge was surrounded by good arable land but relied on its hinterlands for food and fuel supplies. Grain could be sourced nearby (within 10 miles), some meat was sourced from the fens and beyond and fuel and timber were sourced from further afield (10-15+miles), along with imports via waterways (Lee 2003, 2005). However, this period in England was characterised by climate change, war, plagues, and dramatic fluctuations in the economy and population (Campbell 2016). Following national trends, population and economic productivity reached a peak in the early 14th century and was followed by dramatic population decline and economic recession in the early/mid 14th and 15th centuries, before recovery in the 16th century, although archaeological evidence suggests the town showed little evidence for decline or abandonment in the 14th and 15th centuries (Cessford in Robb n.d.).

Figure 1 to Figure 4 illustrate how the town of Cambridge developed from AD 900 to 1500. Following the Norman Conquest, a castle was established on Castle Hill, to the North of the river. Sometime in the 11th to early 12th centuries, the substantial 'King's Ditch' was constructed, forming a prominent feature on the east side of the town (Cessford and Dickens 2019, pp. 45–92). Numerous religious buildings were also founded in Cambridge in the 11th century, including parish churches, as well as an Augustinian Priory (c.1092, later Barnwell Priory) (Roach 1959a) (Figure 2). The 12th century saw a continuing proliferation of religious buildings, including the establishment of The Priory of St Radegund in c.1133 and the Hospital of St John the Evangelist (see Section 4.4.2 for more detail) in c.1190-1200. St Mary Magdalen Chapel was also established just outside of Cambridge in c.1130 and served as a hospital for those with leprosy. A Jewish community was established in Cambridge around c.1144, possibly making it one of the earliest provincial Jewries in England (Dobson 1990, Newman 2008a). However, the Jews were expelled from Cambridge in 1275. A further seven religious houses were established in the 13th century by various religious orders, starting with the Dominicans and the Franciscans in

c.1238 (Figure 3). The origins of Cambridge University start in the 13th century, with a migration of scholars from Oxford in 1208-10. Scholars were initially housed in hostels and the first college, Peterhouse, was not established until 1284. The 14th century was a difficult interval in the history of Cambridgeshire. In the early 14th century, there was Europe-wide crop failure, mass mortality of cattle, and famine. This was followed by the Black Death in 1348-9. Cambridge was certainly affected by these events, which had profound social and economic ramifications. Despite this, six more University colleges were founded in the 14th century (Figure 3). Cambridge encountered significant upheaval during the Peasant's Revolt in 1381, adding to longstanding tensions between the University ('Gown') and the non-University ('Town') (Powell 1896). In 1385, there were severe fires in the town, which may have resulted in migration out of the area, further reducing the town population (Roach 1959a). Despite general economic depression in the 15th century, a further six colleges were founded in the 15th century, including King's (1441) and Queens' (1448) (Figure 4). Large swathes of residential buildings were cleared to build King's College, causing extensive changes to the landscape and layout of the Medieval town. (Roach 1959a). In the 16th century, Cambridge was a key player in the Reformation and during the Dissolution in 1538, most remaining monastic buildings were acquired by private buyers or later subsumed by Colleges.



Figure 1: Cambridge c.AD 900 (map produced by Vikki Herring for the 'After the Plague' project)

[Permission to reproduce the maps by Vikki Herring has been granted by John Robb, Principal Investigator of the 'After the Plague' project]

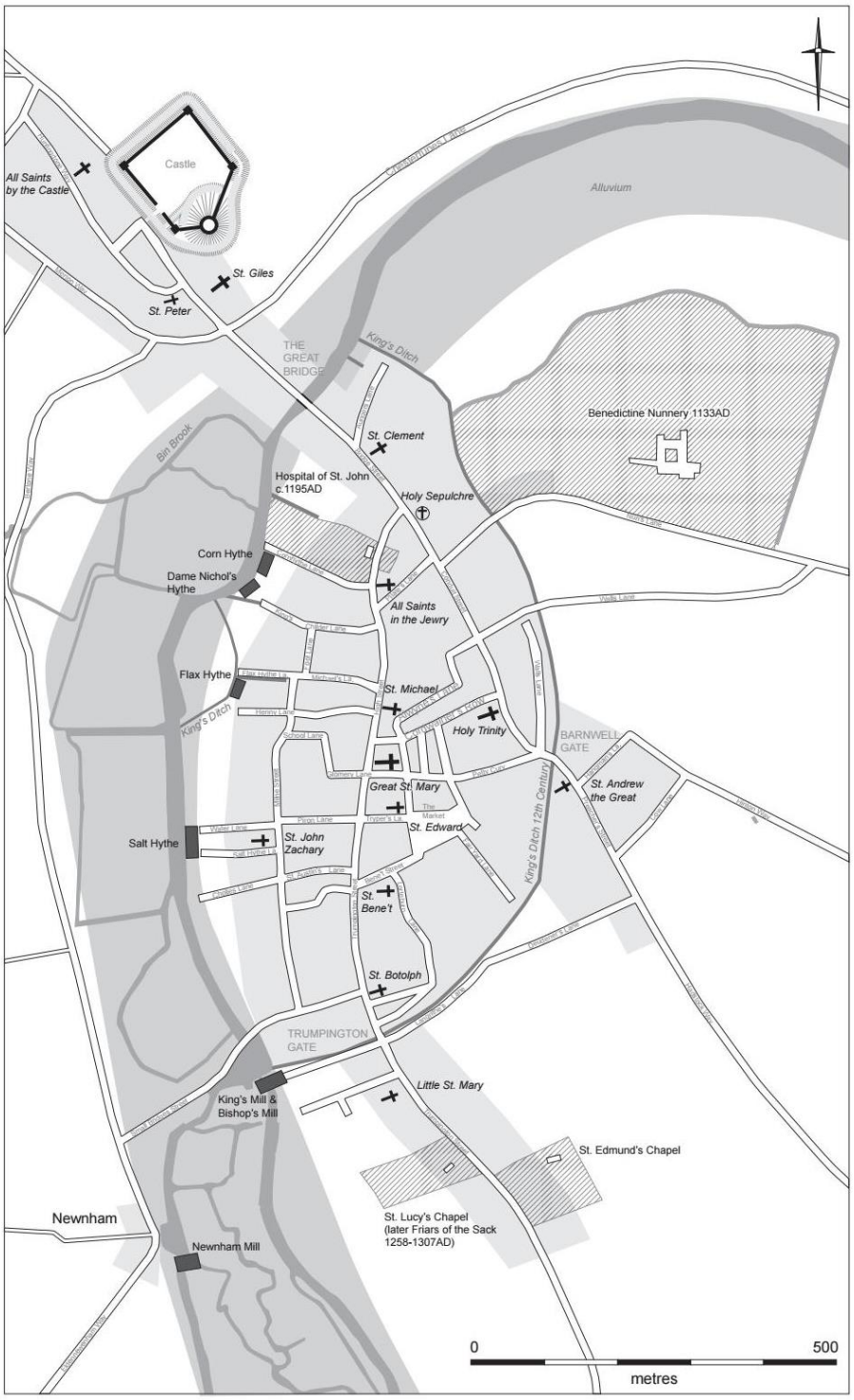


Figure 2: Cambridge c. AD 1200 (map produced by Vikki Herring for the 'After the Plague' project)

[Permission to reproduce the maps by Vikki Herring has been granted by John Robb, Principal Investigator of the 'After the Plague' project]

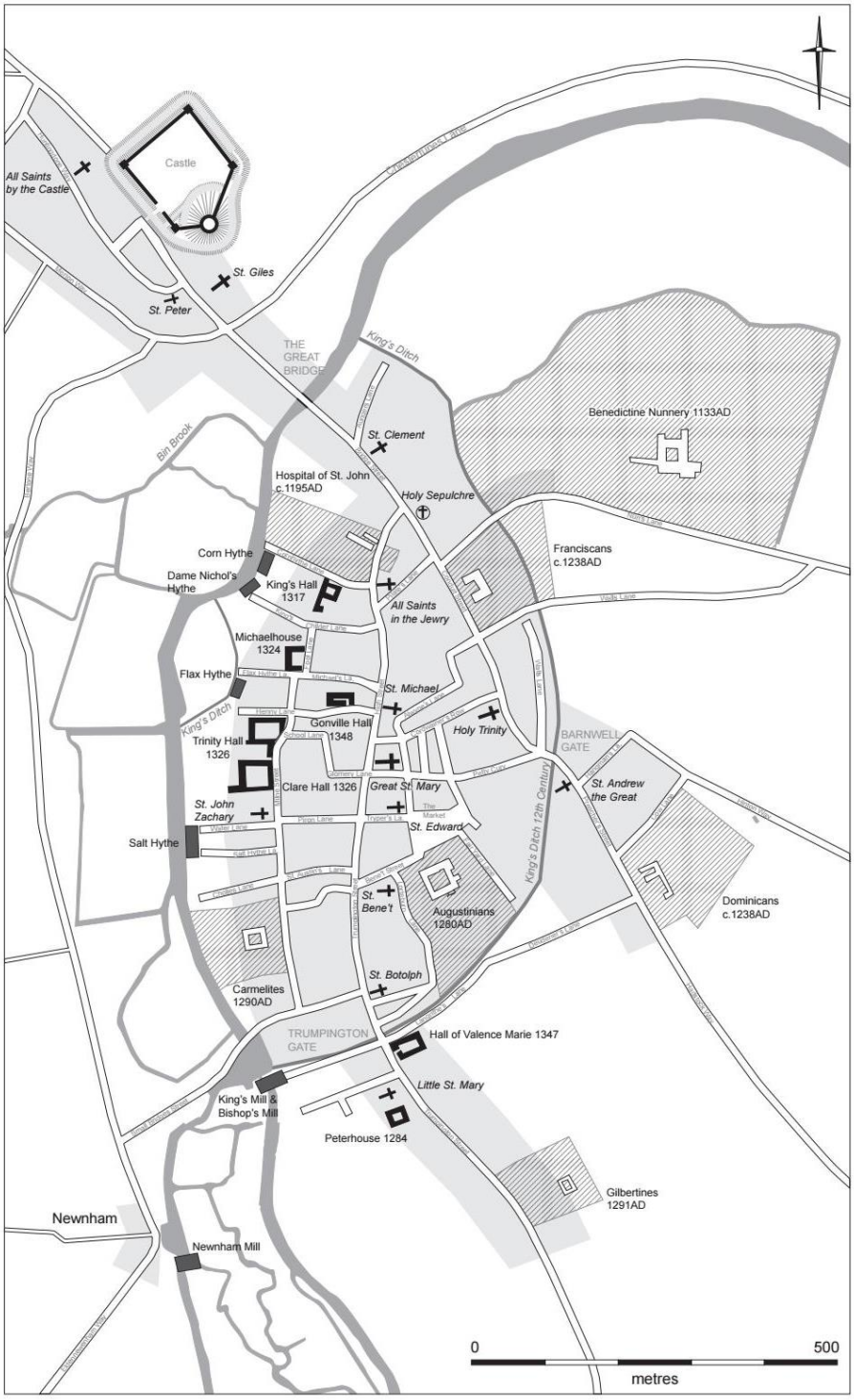


Figure 3: Cambridge c.AD 1350 (map produced by Vikki Herring for the 'After the Plague' project)

[Permission to reproduce the maps by Vikki Herring has been granted by John Robb, Principal Investigator of the 'After the Plague' project]

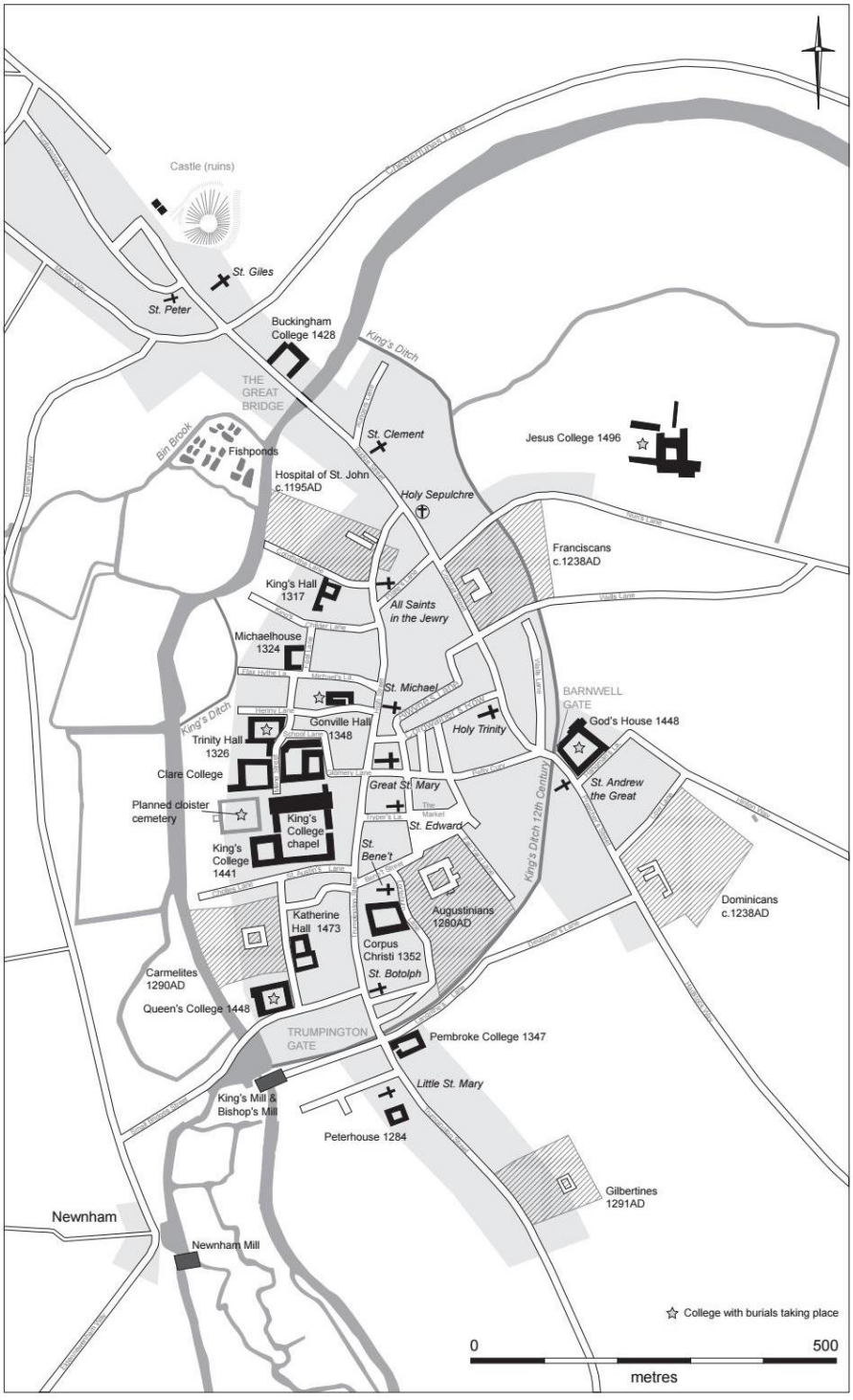


Figure 4: Cambridge c.AD 1500 (map produced by Vikki Herring for the 'After the Plague' project)

[Permission to reproduce the maps by Vikki Herring has been granted by John Robb, Principal Investigator of the 'After the Plague' project]

2.2 Plague and the Black Death

The origin, causes and effects of plagues in the Medieval period are widely debated, with new evidence frequently changing assumptions (Alfani and Murphy 2017). Current knowledge indicates there have been three major global 'waves' of plague – the First Pandemic occurring in the 6th-8th centuries, also known as the Justinianic Plague, the Second Pandemic, beginning in the 14th century and resurging until the 17th-18th century (although recent genetic evidence may indicate that the second Pandemic may have had its origins in the 13th century (Green 2020)), and the Third Pandemic, occurring in the 19th-20th centuries (Green 2014). For the purposes of this thesis, it is the so-called Second Pandemic that is of interest. Documentary evidence indicates the first outbreak of the Second Pandemic, subsequently known as the 'Black Death', began to spread rapidly across Europe in c.1346-7, reaching England in 1348 (Horrox 1994, pp. 10–11). The Black Death was particularly deadly, with estimates of a 60% reduction in the English population in the years afterwards (Benedictow 2004). In some places this led to mass burials, such as those found at East Smithfield, London (Grainger *et al.* 2008) and Thornton Abbey, Lincolnshire (Willmott *et al.* 2020). While the Black Death plague outbreak was only active in England for one to two years, there were many subsequent outbreaks until at least the late 17th century (Appleby 1980). These tended to be more localised and less deadly, but still caused significant disruption. Although previously contested (e.g. Cohn 2003), ancient DNA (aDNA) analysis has now confirmed that the Black Death, and other plague events, were caused by the bacterium *Yersinia pestis* (Haensch *et al.* 2010, Bos *et al.* 2011, Schuenemann *et al.* 2011). Plague can take multiple forms - bubonic plague has a high mortality rate (c.40-60%) but pneumonic has an almost 100% mortality rate and can kill in two to three days (Walløe 2008). In all cases, the disease does not leave traces in archaeological skeletons.

Evidence from archaeological and earth sciences attest to the monumental effects of plagues, disrupting industry, construction and trade (Orton *et al.* 2014, Ljungqvist *et al.* 2018, McConnell *et al.* 2019). The Black Death has been framed as a pivotal moment in history (e.g. Bowsky 1971, Hatcher 1977, Campbell 2016). Various primary sources from the period, including narrative accounts (e.g. The Decameron by Giovanni Boccaccio), manorial court rolls recording deaths of tenants, rents, wages, crop yields etc., subsidy rolls recording taxation, cartularies detailing particular institutions, orders for consecration of new burial grounds, and statutes (e.g. the 1349

Ordinance of Labourers, the Assizes of Bread and Beer) have been drawn upon to characterise the effects of the Black Death (Horrox 1994), indicating the enormous and sustained decline in population and a radically changed social and economic landscape. In general, in the later 14th century, land, property and commodity prices decreased due to surplus and wages increased due to demand, allowing some individuals more purchasing power (Campbell 2016). This potentially improved the standards of living of much of the population (Dyer 1989), and induced dietary change due to subsequent shifts in access, availability and demand (Woolgar *et al.* 2006, see Section 2.3 for more detail). Newly found wealth and bargaining power for the lower classes shook the entrenched social hierarchies, ultimately leading to the decline in serfdom (Hatcher 1977, Campbell 2016). Amongst other effects, this allowed greater freedom of movement, particularly for the lower classes, which alongside the need for re-population, meant that patterns of mobility were also affected by the Black Death (McClure 1979, 2020, Goldberg 1986, Dyer 2000, see Section 2.4 for more detail)

Bioarchaeological studies concerning the effect of the Black Death on Medieval populations have focussed on two approaches: analysing the demography and 'health' of those excavated from Black Death mass graves, or analysing trends across general Medieval cemetery populations, essentially taking a 'before/after the plague' approach (Dewitte 2014, Kacki 2020). The former strategy seeks to directly investigate those who are assumed to have died from the Black Death to identify risk factors and whether the Black Death differentially affected certain groups of people, whereas the latter largely seeks to identify whether the assumed post-Black Death changes in living conditions e.g. more access to certain food products, and social structure e.g. increased social and geographical mobility, can be identified in the skeletal remains (Dewitte 2014, Kacki 2020). The former approach is limited as it requires suitable mass graves, of which few have been identified and excavated. In addition, while these catastrophic cemetery populations are very useful for identifying short term trends, they are extremely limited in providing information about the long-term effects of plague. Research on skeletal remains from British sites has largely followed the former approach, dominated almost solely by research on the East Smithfield Black Death cemetery in London (e.g. Waldron 2001, Margerison and Knüsel 2002, Gowland and Chamberlain 2005, DeWitte and Wood 2008, DeWitte 2009, 2010, 2014a, 2014b, Kendall *et al.* 2013, Klunk *et al.* 2019, Godde *et al.* 2020). However, larger scale 'before/after' type approaches have not yet readily been applied in British bioarchaeology (aside

from DeWitte 2018, Galofré-Vilà *et al.* 2018), although they have been utilised in some studies of European cemeteries (e.g. Yoder 2006, Arcini *et al.* 2016, Zechini 2017).

Stature, pathology and age-at-death in archaeological skeletons have been used to investigate assumed improvements in living conditions and general health after the Black Death. Final achieved stature is the result of genetics, but also childhood living conditions and nutrition (Bogin 2021), therefore studying growth and stature in archaeological skeletons through time can provide information about developmental delays and changes in conditions (Steckel 1995, Galofré-Vilà *et al.* 2018). Broad studies of stature in Medieval England (Galofré-Vilà *et al.* 2018) and Sweden (Arcini *et al.* 2016) have shown that there was a general increase after the Black Death, which has been interpreted as a result of better living conditions and increased access to meat and dairy (Arcini *et al.* 2016, pp. 122–123). However, while Arcini *et al.* found that women showed a greater increase in stature after the Black Death than men (Arcini *et al.* 2016, pp. 122–123), DeWitte found that in London, female stature actually *decreased* after the Black Death, highlighting possible sex-based differences in post-plague experiences (DeWitte 2018, pp. 10–11). Further studies of pathology and age-at-death in London generally indicate improvements in 'survivorship' and health after the Black Death (DeWitte 2014a, 2014b, 2018).

Isotope analysis has not yet frequently been applied to answer questions about the effects of the Black Death. Studies seeking to identify post-plague improvements in diet in the Jutland peninsula of Denmark (Yoder 2006, 2010), Lund, Sweden (Arcini *et al.* 2016) and Berlin, Germany (Zechini 2017) have produced mixed results. While temporal change in the isotope values is present in the Swedish samples, the timings mean that they are not interpreted as a result of the Black Death, but rather other social and cultural shifts in the Medieval period (Arcini *et al.* 2016). Little temporal change at all is seen in sites in Denmark (Yoder 2006, 2010), although a slight decrease in carbon isotope values in skeletons dated to 1300-75 from Ribe are interpreted as potentially being the result of trade disruption due to the Black Death (Yoder 2006, p. 228), or taboos preventing the consumption of marine fish during a plague (Yoder 2010, p. 2234). In Berlin, a post-1350 increase in nitrogen isotope values was observed and attributed to increased animal protein consumption following the Black Death (Zechini 2017, p. 58), however, the post-Black Death sample consisted of skeletons dating from 1400-1700, so directly attributing the observed changes to the effects of the Black Death is tenuous. Studies of

the effect of the Black Death on migration using isotope analysis are even more uncommon, although strontium isotope analyses of individuals from Trinitatis cemetery, Lund showed least population variability in the 1350-70 period, directly following the Black Death, perhaps indicating a collapse of trade and migration in response to the pandemic (Arcini *et al.* 2016, p. 129).

2.2.1 Plague in Cambridge

There is relatively little primary documentary evidence for the impact of plague in Late Medieval Cambridge. The population of Cambridge in the early 14th century has been estimated to be c.5800 (Casson *et al.* 2020, p. 318). A true estimate of the mortality rate for the town is unknown but following estimates of up to 60% mortality from other studies (e.g. Benedictow 2004, Sloane 2011) and up to 70% mortality in certain groups in Cambridgeshire (e.g. Oakington, see Cessford in Robb n.d.), between 1700-3500 people in Cambridge alone may have died as a result of the 1349 plague outbreak (Cessford in Robb n.d.). Some records from colleges and religious establishments attest to excess mortality in Cambridge in 1349, likely related to the Black Death. The list of masters of the Hospital of St John shows the death and replacement of three masters between May and June 1349 (Rubin 1987, p. 302). 16 of the 40 scholars who were resident at King's Hall were also recorded to have died between April and August 1349, although this may be an underestimate (Roach 1959b). The only convincing archaeological evidence for a 14th-century mass burial in Cambridge was found at St Bene't's (Cessford and Fallon 2006) (see Section 4.4.2). The mass grave was incorporated into the layout of Corpus Christi College, possibly so the college could commemorate the victims (Cessford in Robb n.d.). No other evidence of Late Medieval 'plague pits' have been found in Cambridge and while their existence cannot be ruled out, this suggests that the plague dead were largely afforded normal burial rites, which may indicate that deaths did not overwhelm the town infrastructures. Outside of Cambridge, documentary evidence from manors and Bishop's registers indicate mass mortality was experienced throughout Cambridgeshire in 1349-50. Estimates for mortality at Oakington, approximately 8km Northwest of Cambridge, are as high as 70% (35/50 residents), while other nearby sites – Dry Drayton and Cottenham - had estimated mortalities between 48-49% (Page 1934, Ravensdale 1985, Aberth 1995). Calculations from episcopal registers for the diocese of Ely, which would have covered much of modern

Cambridgeshire, indicate a mortality rate of 47% in 1349-50 (Aberth 1995). Test pits excavated in Cambridgeshire villages potentially indicate dramatic Late Medieval demographic decline and settlement contraction though the distinctly lower percentage of test pits containing Late Medieval pottery than High Medieval pottery (overall 44% less test pits with 2-4+ sherds of Late Medieval pottery) (Lewis 2016, pp. 782–784). However, some of these reductions could be related to changes and increased diversity in cooking vessels (McCarthy and Brooks 1988, Cessford pers comm).

There is little direct documentary or archaeological evidence of the subsequent plague outbreaks in the 14th and 15th century in Cambridge, although it was certainly affected, with further records from King's Hall, for example, showing a large number of deaths of scholars in 1361 (Roach 1959b). Plague is explicitly mentioned in documents from the 16th century onwards, with records of colleges regularly closing down during outbreaks (Williamson 1957).

Analysis of pathogen aDNA carried out on High/Late Medieval skeletons as part of the 'After the Plague' project provides further evidence for plague in Cambridgeshire (Scheib in Robb n.d.) (Table 1). It confirms that St Bene't's is likely to have been a mass grave for plague victims, with two of the four skeletons who were screened for the presence of *Y. pestis* aDNA giving positive results. Only a few of the skeletons from Cambridgeshire who was were positive for *Y.pestis* can be attributed to the Black Death outbreak, although a negative result is not necessarily evidence that an individual did not die of *Y.pestis*, due to factors such as preservation and low pathogen presence in the sample (Scheib in Robb n.d.). All other Cambridge individuals who gave positive or probable results for the presence of *Y.pestis* are either poorly dated or date to the 15th century. The pathogen evidence shows that *Y.pestis* was present in Cambridge and that it killed people over multiple centuries, proving subsequent outbreaks occurred. It also shows that those who died of *Y.pestis* were largely buried in discrete, normative burials in various locations.

PSN	Site Name	Est. Death Date	Burial Type	Sex	Age	aDNA
495	St. Bene't's	1349-77	Mass Grave	Female	18-25yr	Positive
496	St. Bene't's	1349-77	Mass Grave	Male	26-35yr	Positive
497	St. Bene't's	1349-77	Mass Grave	Male	>18yr	Probable
503	Augustinian Friary	1450-1538	Single	Male	13-17yr	Positive
507	Augustinian Friary	1475-1536	Single	Male	7-12yr	Positive
517	Augustinian Friary	1349	Single	Male	26-35yr	Positive
523	Augustinian Friary	1450-1538	Single	Male	18-25yr	Positive
766	All Saints by the Castle	1349-62	Single	Male	46-59yr	Positive
1222	St Mary Clopton	1349-1400	Single	Female	13-17yr	Positive
1268	St Mary Clopton	1349-1561	Poss. Double	Male	26-45yr	Probable
1270	St Mary Clopton	1349-1561	Single	Male	18-25yr	Probable
1272	St Mary Clopton	1349-1561	Single	Male	>60yr	Positive
1274	St Mary Clopton	1349-1561	Single	Male	>60yr	Positive

Table 1: High/Late Medieval individuals from Cambridge who were screened for Yersinia pestis aDNA as part of the 'After the Plague' project and were deemed positive or probable (Scheib in Robb n.d.). *See Section 4.4.2 for more information about the sites.*

2.2.2 Summary of Plague and the Black Death

The Second Pandemic shaped much of life in the Late Medieval period, causing significant social and economic changes. Evidence for the direct effects on everyday life in Cambridge and the surrounding area is patchy. However, the available evidence confirms that plague was present in Cambridgeshire and did cause mass mortality events, which may have had significant subsequent implications for the standards of living in the area.

2.3 High/Late Medieval Diet

Historical and archaeological data indicates that High/Late Medieval diet consisted of grain-based products, predominantly bread, ale and pottage, supplemented with meat, dairy, fish, fruit and vegetables depending on status, season and supply (Woolgar *et al.* 2006). Reviews of Medieval consumption patterns repeatedly refer to the Black Death as a driver of change (e.g. Woolgar *et al.* 2006) and this will be a recurring theme in this section. There are still surprisingly few published large scale isotope studies that have investigated High/Late Medieval diet in Britain (see Müldner 2009 for a review of Medieval isotopic studies in the decade up to 2007), despite that fact that 'medieval historians have recognised the importance of the study of diet and nutrition and its link with medieval society' (Müldner and Richards 2005, p. 39). The studies that have applied isotope analysis to High/Late Medieval skeletal material in Britain are concentrated mainly on Northern England, particularly Yorkshire (e.g. Richards *et al.* 2002, Müldner and Richards 2005, 2007b, 2007a, Roberts *et al.* 2013, Britton *et al.* 2015, Bownes *et al.* 2018, Kancle *et al.* 2018)(see Appendix V for a gazetteer of previous studies). These isotope studies have a range of objectives. Most discuss identifying differentiation in diet according to one or more social, spatial and/or temporal factors. Some studies are primarily concerned with questions of temporal change (e.g. Müldner & Richards 2007a), others have investigated diet relating to particular institutions (e.g. Bownes *et al.* 2018), while others take an osteobiographical approach (e.g. Knüsel *et al.* 2010, Lamb *et al.* 2014). As isotope analysis in archaeology is limited to detecting only certain dietary aspects (see Chapter 3), the focus of the following section will be on the documentary and archaeological evidence for common crop, meat and fish consumption in Cambridge. The section will also incorporate relevant results of previous isotope analyses from High/Late Medieval sites in Britain.

There are several factors that may have caused diet in High/Late Medieval Cambridge to be distinctive. Firstly, the landscape – Cambridge was surrounded by high-quality arable land which was well suited to growing crops. A proportion of the Cambridge hinterland consisted of fenland, which may have been liable to flooding but would have been very fertile (Stone 2012). The extensive waterways around Cambridge allowed for the easy transport and trade of goods, as well as access to freshwater fish and eels (Stone 2012). This meant Cambridge was in a good position to access a variety of food. Secondly, and related to these good transport links,

Cambridge and the surrounding area was host to numerous fairs. Stourbridge Fair was established in the early 13th century and was held annually on land owned by the Leper Hospital of St Mary Magdalen – now Stourbridge Common. The fair was large and of significant importance in Britain (Miller and Hatcher 1995, pp. 166–176). The Midsummer Fair and the Garlic Fair were also established in Cambridge in the 13th century (*ibid.*). A multitude of goods were sold at these fairs and they gave residents access to a wide range of imported foodstuffs, including 'exotic' items. In particular, Stourbridge was important for the purchase of marine fish and spices (Lee 2003). 15th-16th century accounts from King's Hall, Cambridge, indicate that the college purchased 'cod, stockfish, ling, salmon, herring, lob, sturgeon, catfish, and salted eels, together with raisins, prunes, almonds, pepper, dates, cloves, mace, sugar, saffron, and bay salt' from Stourbridge and Midsummer fairs (Lee 2003, p. 259). Thirdly, the social dynamics of High/Late Medieval Cambridge may have had a detectable effect on diet – it is likely to have been highly socially stratified, with the numerous wealthy colleges and religious houses in Cambridge consuming 'high-status' diets which would have been in stark contrast to the other townspeople (Lee 2003).

2.3.1 Production and Consumption

2.3.1.1 Crops

Historical accounts indicate that wheat, barley, rye, oats, peas and beans were the most common crops in Medieval England and were predominantly used for bread, malting and fodder (Stone 2006). Prior to the Black Death, higher status individuals tended to eat bread made with wheat, whereas bread eaten by lower-status individuals tended to utilise a wider variety of grains and was commonly made with rye and barley, sometimes including a proportion of peas and/or beans (Stone 2006). Significant changes in bread consumption are observed after the Black Death, with people seeking out higher quality products (Stone 2006).

In Cambridgeshire, the most important crops were wheat and barley. Farmers tried to mitigate crop failures by planting a mix of autumn/winter sown crops (e.g. wheat) and spring-sown crops (e.g. barley and oats) (Campbell and Gráda 2011, p. 865). The archaeobotanical cereal assemblages from Cambridge contexts are largely typical of the Medieval period in England, with barley and free-threshing wheat being the predominant cereal grain, followed by rye and

oat (Cessford and Dickens 2019, pp. 199–204), although some sites show a conspicuous absence of rye, e.g. Hostel Yard (Simmons 2005).

Peas have been identified at several sites, including 12th-century contexts at the Grand Arcade site and 11th-14th century pre-friary contexts at the New Museums site (Cessford and Dickens 2019, pp. 199–204). Lentils are rare but have been identified at some sites, including 12th-century contexts at the Grand Arcade (Cessford and Dickens 2019, pp. 199–204) and a 14th century pit at Bradwell's Court (de Vareilles 2007). Most vegetables are largely invisible in the archaeobotanical record but evidence for hazelnuts and fruits, including raspberries, strawberries, plums, cherries, figs, pears and apples have been recovered in 11th-14th century contexts in Cambridge, mostly from cess deposits (de Vareilles 2007, Cessford and Dickens 2019, pp. 199–204). Seeds from various condiments such as opium poppy, black mustard, celery and fennel have also been found (Cessford and Dickens 2019, pp. 199–204). Unfortunately, plant macrofossil evidence is limited by issues of differential preservation and subsequent biases in representation, in many cases being reduced to a presence/absence approach. This limits true quantification of consumption from the evidence but the plant macrofossil evidence from Cambridge, particularly from the Grand Arcade site, shows that there was cultivation, processing and consumption (as implied by cess deposits) of a variety of commonly utilised Medieval crops and provides evidence of some of the 'invisible' foods to isotope analysis – fruits, nuts and flavourings.

2.3.1.2 Meat and Dairy

Consumption of meat in the High/Late Medieval period varied greatly according to social status but was also restricted by religion, where avoidance of meat was encouraged on multiple days of the week, as well as religious holidays (Woolgar 2016). Meat formed a small to moderate proportion of the diet of the peasantry, compared to aristocratic and other high-status households, which followed a veritable calendar of meat consumption determined by availability, slaughter patterns and religious holidays (Woolgar 2006a). Birds made up a smaller proportion of the diet than larger domesticates but were an important dietary component (Serjeantson 2006). Chickens and geese were consumed across all social groups but the consumption of many other birds, such as swans and peacocks, was strongly linked to social class and was a conspicuous demonstration of wealth (Serjeantson 2006, Slavin 2009). Eggs and

dairy products were widely consumed, with butter and cheese providing a means of preservation (Woolgar 2006a). Dairy may have been a primary protein source in the absence of regular meat (*ibid.*). After the Black Death, there was more meat stock available per person and an increase in the meat trade and dairying. Food preferences changed across all levels of society, with a shift to greater meat consumption (Woolgar 2006a).

Zooarchaeological data provides evidence for the animals utilised in Cambridge. The faunal bone excavated from Medieval contexts in Cambridge predominantly consist of livestock species (cow, sheep/goat and pig) and the assemblages, particularly from the Grand Arcade site, are typical of Medieval urban sites (Cessford in Robb n.d., Cessford and Dickens 2019, pp. 181–197) (see Section 4.4.2 for more details of the site). Throughout the High/Late Medieval period, at most Cambridge sites, sheep/goat bones form the largest proportion of identified specimens, usually followed by cattle. Pig bones are less frequent, but still form around 20% of the identified specimens at Grand Arcade (Cessford and Dickens 2019, pp. 181–197). Chicken is the most common bird species represented, forming up to 20% of the specimens identified. In Medieval contexts at St John's Triangle, a site near the Cambridge Round Church, some unusual bird species were present, including crane and lapwing, and an increase in consumption of wild birds from the 14th century was also noted at the Grand Arcade, corresponding with national trends in high-status consumption (Serjeantson 2006, Higbee 2008, Cessford and Dickens 2019, p. 186) (see Section 4.4.2 for more details of the site).

Zooarchaeological assemblages offer a snapshot of the waste disposed but proportions of bones found cannot be directly equated to the proportion of consumption, especially as many animals would have been kept for secondary products, such as milk, eggs, leather and wool, and cattle could also be used for traction. Calculation of meat weight estimates for livestock, using the amount of meat available based on the minimum number of individuals (MNI) of each species present, goes some way to tackle this. Calculations of the proportion of meats (beef, mutton and pork) consumed in Cambridge through the High/Late Medieval period indicate consumption patterns differed between urban and rural sites and changed through time (Cessford in Robb n.d., Cessford and Dickens 2019, pp. 181–197). Beef consumption generally predominated in both urban and rural sites, except in High Medieval domestic town contexts, where mutton dominated. Beef consumption was more prevalent in the rural villages than the

town sites. Pork was consumed in the smallest proportion in most cases, but consumption was highest in collegiate and religious sites in the Late Medieval period (Cessford and Dickens 2019, pp. 181–197). Overall, the zooarchaeological evidence from Cambridge indicates that beef and mutton were the most prevalent meats and pork was consumed to a lesser degree. Chicken was the most consumed bird, but eggs were also important. Differences between urban and rural consumption were present and there is evidence for social stratification in meat consumption within Cambridge, particularly at colleges and religious sites.

2.3.1.3 Fish

Fish was an important component of Medieval diet, particularly as it could be consumed during periods of religious prohibition of meat consumption (Serjeantson and Woolgar 2006). Freshwater, marine and diadromous (both freshwater and marine) fish were consumed, with marine fish becoming increasingly dominant in the Late Medieval period (Barrett *et al.* 2004). As the aristocracy and other high-status households tended to eat meat more regularly than the rest of society, it translates that they also consumed a higher quantity of fish as a substitute on their non-meat days (Dyer 2000). A plentiful supply of freshwater fish was facilitated by constructing and maintaining fishponds, therefore regular consumption of freshwater fish was generally reserved for the wealthier, landed members of society (*ibid.*). Marine fish was eaten fresh but was predominantly supplied preserved – either smoked, cured, salted, brined or air-dried. This means it could be widely transported and stored without spoiling, making it more accessible and affordable across society. Unlike for meat, for example, there is less historical evidence for the Black Death having an impact on fish consumption, although the quantity of fish consumed may have decreased with increasing consumption of meat in the Late 14th century (Serjeantson and Woolgar 2006). In the few years immediately after 1350, the types of fish consumed may have changed due to disruption to imports, leading to a temporary increase in exploitation of local freshwater fish (Orton *et al.* 2014).

Isotope studies have detected differences and changes in marine fish consumption in Medieval Britain (Müldner 2016). For example, analysis of humans in York from sites ranging from the Romano-British period (2nd-4th centuries) to the Post-Medieval period (19th century) showed statistically significant differences in human isotope values through time, with values suggesting

that Late Medieval individuals had a much higher contribution of marine products in their diet than High Medieval individuals.

Fish bone recovered from English archaeological sites across the Early to Late Medieval period indicate that assemblages from the earlier periods are dominated by freshwater and diadromous fish – cyprinids and eels (Barrett *et al.* 2004). After the 11th century, marine fish, mostly herring and gadids, become increasingly dominant. At some sites, there is evidence that this switch to marine fish happened well within a 100yr period, centred around AD 1000, pre-dating the Norman Conquest (Barrett *et al.* 2004). This is dubbed the 'fish event horizon', marking key developments in trade, economics and urbanisation (Barrett *et al.* 2004). Following this, isotope analysis has shown that in the High Medieval period, marine fish consumed in England was largely fished from the southern North Sea, but imports from further afield were increasingly predominant from the 14th century, highlighting expanding supply and demand (Barrett *et al.* 2011).

Fish bone from Medieval contexts in Cambridge comprises of a wide variety of freshwater and marine species, as well as eel, smelt and Salmonidae which could be either freshwater or marine (Harland 2008, 2009, Cessford and Dickens 2019, pp. 197–199). In keeping with the general English trend, at the Grand Arcade site, herring and whiting are by far the most dominant species in the 12th and 14th century contexts, although this changes to eel in the 16th-century contexts (Cessford and Dickens 2019, pp. 197–199). Herring makes up 80% of the assemblage at Hostel Yard in the 14th century but drops to 45% in the 16th century, on par with eel (46%) (Harland 2008). Fish bone recovered from St John's Triangle site, Cambridge, shows dominance of herring in the 14th-16th centuries, but also shows continued exploitation of eel from the 10th to 16th centuries, as well as a surprisingly high proportion of freshwater Cyprinidae in the 16th century (Harland 2009). While proportions of fish bone by species cannot directly imply proportions of consumption, mostly due to differential preservation and disposal, the assemblages generally show the dominance of marine resources in High/Late Medieval period in Cambridge but also highlight the importance of eels and the continued use of freshwater fish which could have been caught in the River Cam or the Great Ouse, or from fishponds (Harland 2008, 2009, Cessford and Dickens 2019, pp. 197–199).

2.3.1.4 Famine

There were periods of severe disruption to food production across High/Late Medieval England that would have affected Cambridge. High population combined with extreme weather and warfare resulted in famines (Slavin 2014, Alfani and Ó Gráda 2018). One of the most catastrophic events was the 'Great European Famine' in 1315-1322, resulting in the death of c.10-15% of the population of England (Slavin 2014). This famine arose from torrential rain, flooding and colder temperatures over multiple seasons, causing repeated crop failures (Slavin 2016, Alfani and Ó Gráda 2018). Calculations of shortfalls of grains over multiple years shows that there was a 25% reduction in yield in 1315, increasing to 47% in 1316, the largest shortfall recorded between 1268-1480 (Campbell and Gráda 2011, p. 869). Concurrent with these crop shortages were sheep and cattle murrains, including the 'Great Bovine Pestilence' – a panzootic event that reached England by 1319, resulting in the death of an average of 62% of demesne cattle in England and Wales (Slavin 2012, p. 1242). The bovine population did not recover for several decades, having an effect not only on meat and dairy supplies, potentially leading to a 'protein famine', but also on traction and crop manuring (Slavin 2012). Chroniclers' accounts for Eastern England between 1250-1350 attest to the fluctuations in harvests and food supply, recording 'dearths' in 1256, 1289-1290 and 1295, famines in 1257-1258, 1271-1272, 1293-1294 and the Great Famine in 1315-1321 (Hallam 1984). However, the experience of these events appears to be more complicated on a local level, with manorial accounts often not matching the chroniclers' impressions (*ibid.*), meaning some areas may not have been as affected by famine events as others.

2.3.2 Social Groups

High/Late Medieval diet was likely to have differed depending on various economic and social factors. Social status and stratification had a huge impact on the types of foods consumed, with upper classes employing conspicuous, even competitive, consumption with greater quantities and varieties of meats and fish (Dyer 1989, Woolgar *et al.* 2006). In Cambridge, there was certainly 'Town' versus 'Gown' (university) social stratification. In the Late Medieval period, many of the colleges were wealthy, allowing them access to a varied and expensive diet, more akin to aristocrats than townspeople (Lee 2003, p. 93). Luxury items purchased at the fairs were consumed, along with a higher than average proportion and variety of meats and fish (*ibid.*).

Religion also heavily influenced High/Late Medieval diet, principally through Christian beliefs advocating periods of fasting and abstinence from meat (Woolgar 2006b). These religious advocations were observed to varying degrees depending on an individual's piety (*ibid.*). There were exemptions – 'those below the age of 21, pregnant women, the elderly, the sick, and the poor, as well as those whose work involved hard manual labour' (Woolgar 2006b, p. 192). Most monastic orders followed a diet based on the Rule of St Benedict. This, along with the communal institutional environments, created a degree of homogeneity to religious consumption (Woolgar 2006b). Diet was supposed to be largely vegetarian, avoiding the flesh of quadrupeds, but various orders interpreted this differently, allowing meat (or substitutes) to varying degrees. Luxury consumption was compatible with religious adherence (Woolgar 2006b, p. 200) and generally, the consumption of some religious orders was akin to a high-status diet. This can be seen in the case study of the Cambridge Hospital of St John below – although it was not a particularly wealthy institution compared to other religious houses and colleges in Cambridge, the foods purchased are indicative of a varied and relatively meat-rich diet.

Isotope analysis can be effective at investigating differences in diet by social group (Müldner 2009). However, an early isotope study aimed at investigating a variety of contemporary Late Medieval social groups with differing wealth, status and occupations from Northern England showed surprisingly little variation in isotope values based on social status but did show a difference compared to previously published Roman and Anglo-Saxon data emphasising the importance of aquatic food sources in the High/Late Medieval diet (Müldner and Richards 2005). Other studies have demonstrated convincing differences by social group, particularly

monastic groups with distinctive isotope signatures due to greater marine fish consumption (Müldner and Richards 2007a, Müldner *et al.* 2009). At extreme ends of the social strata, two very high-status individuals – King Richard III and Lady Maud de Lacy ('St Bees Lady') have been shown to have distinctive dietary isotope signatures in keeping with diets considerably enriched in meat and fish (Knüsel *et al.* 2010, Lamb *et al.* 2014), while isotope values from individuals from the rural village of Wharram Percy are often used as an example of peasant diet, with little evidence for aquatic foods (Richards *et al.* 2002, Fuller *et al.* 2003, Müldner and Richards 2006).

2.3.2.1 Diet at the Hospital of St John, Cambridge, a Case-Study

Historical documents from the Hospital of St John provide some insight into consumption in a religious institution in Late Medieval Cambridge (Rubin 1987, Underwood 2008). The Hospital was a charitable establishment (see Section 4.4.2) and provided food for residents and staff. It adopted the Augustinian Rule in c.1250 and while diet generally adhered to religious rules, there was some stratification. The brethren were allowed meat three days a week. Diet for residents may have been more basic, but they probably also ate meat on these days, with dispensations for extra meat to fortify the sick (Rubin 1987, p. 160). Those residing in the Hospital with a corrody may have afforded a more varied diet (*ibid.*).

Lists of daily spending on food items for the Hospital cover approximately 22 weeks in 1343-4 (Underwood 2008). Many of the weeks recorded include religious events such as Easter and therefore may not be typical, as there could be large differences in diet during religious festivals (Clay 1966). The type of food varies by week. For example, throughout most of March 1344, no meat at all was purchased, only fish. Almost all the pork and piglet mentioned was purchased in October 1343 as can be seen in an example week listed below (probably 10th – 17th October 1343):

Saturday	Whiting, beef, mutton, kitchen knife
Sunday	Piglet, pork, wastel bread
Monday	From existing household stock
Tuesday	Beef, pork, mutton
Wednesday	Herring, eggs, oatmeal made into flour, eggs
Thursday	Beef, pork, mutton
Friday	Red herring, roach
Saturday	Ling, herring, beef, mutton, piglet

In contrast, a much larger proportion of dairy products were purchased in May and June 1344, as can be seen in the week listed below (probably 22nd – 28th May 1344):

Saturday	Perch, beef, veal, salted fish, herring, mackerel,
Sunday (Pentecost)	Dove/pigeon, milk
Monday	Flour, beef, veal, milk
Tuesday	Beef, veal, milk
Wednesday	Eggs, butter, milk
Thursday	Beef, veal,
Friday	Eggs, mackerel, gruel made from porridge oats/porridge
Saturday	Mackerel, perch, beef and veal

Estimates of the frequency that each item was listed over the 22 weeks (Table 2) reveal that beef and veal were the most frequently purchased meats, and that pork and piglet were purchased infrequently. A large quantity and variety of fish and shellfish was purchased, with the majority being herring and eel. Animal proteins such as eggs, milk and butter were also purchased but there is no mention of cheese. Some other common foods are not listed, which may indicate that the Hospital was partially self-sufficient, producing their own foods such as fruits, vegetables, eggs and bread. Seasonings are recorded as being purchased in September at the Stourbridge and St Ives fairs, indicating seasonal access and the importance of trade. 'Wastel' bread is also listed – this was a high-quality wheat flour product (Woolgar 2016, p. 62), indicating the Hospital was an institution that could afford such products in the early 14th century.

Meat	Beef (40), veal (22), mutton (16), piglet (5), pork (3), ox (3)
Bird	Dove/pigeon (7), chicken (3), pullet/young chicken (2), goose (1)
Saltwater Fish	Herring (32), mackerel (11), ling (8), plaice? (8), whiting (3), red herring (2), white herring (1)
Freshwater Fish	Roach (11), perch (10)
Other Fish	Eel (20), salmon (4), salted fish (7), 'fresh' fish (5)
Shellfish	Mussels (13), cockles (1)
Animal Products	Eggs (17), milk (11), butter (6)
Grains/grain products	Wastel bread (6), oats (1?), flour (1), oatmeal made into flour (2), gruel/porridge (3?)
Fruit/other	Almonds (2), figs (1), raisins (1)
Seasoning	Saffron (2), salt (1), pepper (1), cumin (1)
Other	Fleabane (3)

Table 2: Summary of foods listed in the accounts of the Hospital of St John for approximately 22 weeks in 1343-44, with approximate frequency of mentions of each food calculated in brackets

2.3.3 Sex and Diet

Assessing whether there were differences in diet between males and females is less tangible from the historical and archaeological evidence. In the High/Late Medieval period, women were associated with food preparation (Bynum 1985, Gilchrist 1999). Bynum implies that Medieval culture framed women as food producers and distributors but framed men as the primary consumers, using evidence of segregated banquets with women as observers to the consumption of men (Bynum 1985). These social distinctions clearly could have implications for access to foodstuffs. Diet played a much more central role in women's piety than men, with extreme fasting being a common theme in stories of religious women (Bynum 1985). Bynum suggests that the strong association of women with food preparation and their potentially limited social status naturally lent women to turn to controlling their consumption as an expression of their faith, using a quote from a chronicler: 'holy women gave up food because they had nothing else to give up' (Bynum 1985, p. 10).

Male and female bodies were also understood to be very different in the context of Medieval theories of medicine and health (Gilchrist 2012). Within the framework of humoral theory, men were considered 'hot and dry' and women were considered 'cold and wet'. This affected ideas about how males and females consumed food and the types of foods that they should be eating, particularly when treating an imbalance of the humours. Meat was often prescribed to men but women were told to avoid it where possible, with lighter foods such as fruit and dairy being recommended (Gilchrist 2012, p. 33). How far humoral theory was applied in everyday life is contested but in Hospital settings, sex may have played a key role in dietary provision.

Sex and diet in the High/Late Medieval period has been studied a little using isotope analysis (Müldner 2009). Although the themes above have been explored when explaining differences between isotope values of males and females at St Andrew's Fishergate, York, the explanations steered towards conspicuous consumption in males rather than restriction in females, or simply differences between lay and monastic burials within the cemetery (Müldner and Richards 2007a, Müldner 2009). There was no overall difference between isotope values for males and females at St Mary Spital and St Nicholas Shambles, London, but a group of young females (c.18-25yr) were outliers- some other explanations were explored – including ideas regarding specific diets

for pregnant women or 'young maidens' but the author indicates it was most likely evidence of women who had recently migrated from an area with a different diet (Lakin 2009, pp. 157–9).

2.3.4 Summary of High/Late Medieval Diet

The evidence indicates that the diet in Medieval Cambridgeshire would have been heavily grain-based. Meat was consumed but quantities were highly dependent on social status, although domestic birds were consumed across the spectra. Beef, veal and mutton were common meats, with pork being more infrequent. Freshwater, diadromous and marine fish would have been consumed, most commonly herring and eel. Documentary evidence shows a varying amount of eggs and dairy products were also eaten. Cambridge and Cambridgeshire were well connected, and residents would have had access to imported goods through fairs.

Historical and isotopic evidence from Britain suggests that diet was different for different social groups and changed throughout the High/Late Medieval period. There were crop failures and animal murrains which would have altered diets but there were also advances in trade networks, particularly expanding access to marine fish. Tastes and fashions would have also changed over time, particularly for high-status households. Most importantly, historians attest to the effects that the Black Death had on diet, allowing people to source better quality food and more meat.

2.4 High/Late Medieval Mobility

People in the High/Late Medieval period moved around for a variety of reasons: these could be economical e.g. for employment or trade, social e.g. marriage, religious e.g. for pilgrimage or even political e.g. warfare or displacement (Childs 2006, Ormrod *et al.* 2019). Population mobility and migration in the High/Late Medieval period is a much less tangible subject than diet to identify using archaeological evidence and so research is generally heavily reliant on historical documents. Genetic and isotopic analysis are well placed to contribute to knowledge in this area although these are comparatively new and expensive methods. To date, relatively few isotope studies have investigated mobility and migration in High/Late Medieval Britain and the number of individuals sampled is small (Jobling and Millard 2020) (see Appendix V for a gazetteer). Isotope analysis in this context is limited to comparing the place in which a person died with the place in which they were likely to have spent their childhood (this will be explained further in Chapter 3). Therefore, temporary travel events or multiple migrations are largely invisible. Analysis is better suited to identifying those who are likely to have remained local to their childhood home, or those whose values are distinctly different to the vicinity of their burial. Analysis of King Richard III is a complex example of this- from historical evidence, it is known that he was born in Northampton, spent his childhood in Ludlow and spent much of his adulthood in Eastern England. Once king, he travelled often, lived in London and Yorkshire and was buried in Leicester. Isotope analysis corroborated that he was not local to Leicester and that he could have spent his childhood in the area of Ludlow castle, but his place of birth and travels were invisible (Lamb *et al.* 2014). Other isotope studies of High/Late Medieval skeletons in Britain have mainly been carried out on unknown individuals and the large majority appear to be local to their burial place. Of the individuals identified as non-local, most were likely to have spent their childhoods in England (Lakin 2009, Kendall *et al.* 2013). It has been proposed from isotopic and historical evidence that four Late Medieval individuals from Hull may have been migrants from the Baltic, although this has been questioned (Jobling and Millard 2020). While current samples are generally small, the isotope data does seem more varied in urban sites, e.g. London (Lakin 2009, Kendall *et al.* 2013) than the rural village of Wharram Percy, where only one individual showed evidence of short-distance migration (Mays *et al.* 2017).

The following sections will discuss key drivers for mobility and migration in the High/Late Medieval period, along with the current available historical and archaeological evidence from Cambridge. Due to the limitations of isotope analysis outlined above, while reasons for travel are discussed, the focus will be on migration.

For the purposes of this discussion, travel, with assumptions of impermanence and return, is considered to be different from migration, although of course people could die and be buried in a different place to their birth during travels. Migration is assumed to mean a relocation of residence, possibly across a border of significance, although this is not always assumed to be permanent (Kleinschmidt 2003, Ormrod *et al.* 2019). Scales of 'otherness' in the Medieval period should also be noted - 'strangers' or 'foreigners' could largely be anyone from outside the locality, whether they were from a neighbouring village, or another country. The term 'alien' had specific legal meanings, formally relating to people who owed no direct allegiance to the sovereign power of the country (Ormrod *et al.* 2019, p. 8).

2.4.1 Travel

Travelling in High/Late Medieval England was probably more frequent and less difficult than assumed and most people would have exercised a degree of mobility (Childs 2006). Cambridgeshire has easily navigable, flat terrain and had access to important settlements such as Norwich and London via major routeways (Stenton 1936). A historical account documenting travels of Cambridge scholars in 1319 indicates that a winter journey from Cambridge to York, for example, took five days by horse (Stenton 1936). The waterways of Cambridge also provided means to move people and goods.

In High/Late Medieval England, people regularly travelled to markets and fairs (Dyer 2020). The fairs in Cambridgeshire, in particular, would have attracted people from great distances. Merchants travelled from further afield, with the expansion of sea trade in the Late Medieval period allowing English merchants to trade with much of Europe, and conversely, for foreign merchants to import goods, particularly the Italians and the Hansards (Ormrod *et al.* 2019). Those with specialist skills, such as stonemasons, would have travelled on commission (Childs 2006). People may also have travelled for war or were displaced by war. Warfare with Scotland, Wales and France was ongoing during the High/Late Medieval period and therefore cohorts of

soldiers were recruited from across the country and deployed where necessary (Childs 2006). Royal and governmental officials would also have reason to travel frequently (*ibid.*). The clergy undertook much travel in order to perform duties for the Church. This could be international, particularly to Rome, or localised, performing duties within their diocese (Childs 2006). Religious orders often had houses across Europe and members would travel to others, particularly for education (*ibid.*). The Augustinian Friary in Cambridge, for example, was one of only a few *studium generale* in Europe and attracted local and international scholars (Roth 1958) (see Section 4.4.2). In the Late Medieval period, people also travelled for religious pilgrimage. The majority consisted of short journeys to local and regional pilgrim sites, while others consisted of longer journeys to national sites such as Canterbury and Walsingham (Duffy 2006). Some people undertook much more significant journeys to important Christian pilgrim centres, particularly Santiago de Compostela, Rome and Jerusalem (Duffy 2006, p. 315).

2.4.1.1 John Capgrave: a Case Study

John Capgrave is a fascinating example of the life of a mobile Late Medieval East Anglian (see Fredeman 1979 for a full account). John Capgrave was born in 1393, probably around Lynn, Norfolk. He joined the Augustinian order in Lynn c.1403-10, aged c.17 years. After his novitiate, it is likely that Capgrave undertook three years of study at a *stadium particulare* in Norwich before returning to Lynn for two years. He then moved to London to continue studies at the Augustinian *studium generale provinciae* between 1417-22. Capgrave was then accepted into the Augustinian *studium generalis ordinis* at Cambridge where he studied to become a magister until 1427. He was elected prior in Lynn by 1446. During this role he would have travelled to inspect the 30 friaries of the province. Sometime between 1449-50, Capgrave undertook a pilgrimage to Rome, which may have taken well over a year. He was prior provincial at Winchester between 1453-7 and died in Lynn in 1464, aged 71. The life of John Capgrave was not typical of most Late Medieval people, indeed Capgrave was an accomplished scholar and his story is probably not even typical of many members of the Augustinian order. However, it is an interesting case study for mobility in the Medieval period. From the historical accounts, it appears that he resided in several different towns and cities during his lifetime and must have visited many more through his travels and duties, although he ultimately retired and died in the locality of his birthplace.

2.4.2 Migration

Migration was a 'push and pull' phenomenon (Ormrod *et al.* 2019, p. 2), but a common motive was 'betterment' – employment opportunities, education and marriage (Dyer 2020, p. 263). Migration could be long or short distance and involved localised mobility, as well as immigration of aliens (Ormrod *et al.* 2019). During the High Medieval period, the population was increasing, and urban centres were expanding. Towns in England were built upon constant immigration and huge amounts of rural to urban migration occurred, with perhaps 150,000 people moving into towns in England in the 13th century (Dyer 2020, p. 239, Jones 2020). Population decline and labour shortages after the Black Death transformed the landscape and patterns of migration – poorer land was abandoned, villages were deserted and rural-urban migration was required to fill roles in urban centres (McClure 1979, Goldberg 1986, Dyer 2000). Depending on the circumstances in their own country, the resultant increase in purchasing power in the late 14th century was also attractive to groups outside of England, prompting increased immigration (Ormrod *et al.* 2019, p. 4).

The motivations and opportunities for travel and migration would have differed for males and females. Ratios of men to women differed between rural and urban settlements, with a greater ratio of women in towns (Kowaleski 2014). This has been explained by higher female rural to urban migration (Goldberg 1986). This was primarily for employment, particularly for single women. The service industry, provision of food, roles related to cloth and garments and brewing were common female occupations (*ibid.*). Marriage was also a common reason for migration and women were actively encouraged by the Church and by social norms to marry outside of their home locality. This was particularly common in rural areas and so women were likely to migrate away from where they were born (Dyer 2020). It has been argued that the period after the Black Death presented a 'Golden Age' for women (Barron 1989), with increased economic opportunities and freedoms leading to increased migration, particularly to fill roles in towns (Goldberg 1986), however others have countered that this was not the case for many women (Mate 1998, Lambert 2020).

Historical records of given names and bynames (surnames) are often used to study migration (McClure 1979, 2020). After the Norman Conquest, it became increasingly popular to attribute ethnic or toponymic bynames to people, which could identify their, or their family's, origins

(McClure 2020, p. 123). This type of data comes with heavy caveats. For example, names could be hereditary so didn't necessarily record first-degree migration. Recording of names was also not necessarily accurate or standardised (McClure 2020, p. 125). Nonetheless, analysis of bynames from towns and rural settlements have shown varied mobility, for example the primary catchment areas (area of which c.50% of the names derive) in the early 14th century have been calculated as c.11km for rural Nottinghamshire, c.15-24km for Nottingham, 24-32km for Norwich, c.32km for York and over 64km for London (McClure 1979, pp. 176–177) (conversion from miles to kilometres by the author). Analysis of rural migration in the West Midlands has shown that the majority of journeys individuals travelled were within 15km of their hometown (Dyer 2020, p. 263). An apparent large increase in the primary catchment area of York in the later 14th century byname evidence has been attributed to the Black Death leading to increased mobility and demand for rural-urban migration (McClure 1979, pp. 181–182, 2020, p. 141). Analysis of the surviving documentary evidence for Cambridge indicates that most toponymic surnames in the High/Late Medieval period are derived from 20-30 places in Cambridgeshire, as well as Norfolk and Suffolk. Other English Counties, predominantly in the south, are alluded to, as well as one or two potentially French names (Cessford in Robb n.d.).

2.4.2.1 Aliens in Cambridge

The documentation of the 'alien subsidies' collected sporadically between 1440 and 1487 provide information regarding aliens in England (England's Immigrants 1330-1550, version 1.0 2020). The alien subsidy was a poll tax specifically for residents in England who were from anywhere outside of England, excluding Wales (Ormrod *et al.* 2019, p. 45). The tax was partially to raise money but also to provide a crude method of documenting 'aliens' at a time of political unrest. The tax applied to all first-generation alien residents over the age of 12 and so provides information for men and women across the social strata. There were exemptions, which could hide 'true' numbers of resident aliens – these included clergy (but not parish clergy), alien wives of English men, alien wives of alien men, members of the Hanseatic League and members of Oxford and Cambridge University (Ormrod *et al.* 2019, p. 46).

Alien subsidy documentation for Cambridge provides invaluable information about the population demographic in the Late Medieval period. The 1440 subsidy is the best documented for the area and so the discussion will focus on this. The total number of aliens assessed in 1440

in Cambridgeshire as a whole was 158, with the total number in Cambridge being 67 (England's Immigrants 1330-1550, version 1.0 2020). Estimations by Ormrod *et al.* (2019, p. 62) indicate that approximately 3.53% of *all* taxpayers in Cambridge in the late 14th century were aliens. This figure is lower than their estimates for important Medieval port towns, e.g. Bristol (10.21%), but above their estimates for some other inland towns and cities, e.g. York (1.15%) or Norwich (2.13%), and well above the national average (c.1.0-1.5%) (Ormrod *et al.* 2019, pp. 61–63). Of the 67 aliens taxed in Cambridge in 1440, the nationality of 63 can be estimated based on documented origin and/or surname (England's Immigrants 1330-1550, version 1.0 2020). The majority of the aliens were recorded as 'Dutch' (44/67=65.7%), followed by Irish (6/67=9.0%) and then French (4/67=4.0%) (Table 3). 'Dutch' was a catch-all term for the Low Countries and Germany, but some areas were given more specific labels, such as 'Brabanters' or 'Flemish'. Of the 67 taxed, 50 had a primary occupation listed. The majority were listed as cordwainers – shoemakers. Cobbler, currier and patternmaker were also occupations related to shoemaking, meaning 30/48 (62.5%) males with listed occupations were involved in shoemaking. Almost all of these individuals were listed as 'Dutch' indicating the majority of the 'aliens' in Cambridge in the mid-15th century formed a relatively significant collective of artisan Dutch shoemakers (Ormrod *et al.* 2019, p. 131). Only two women are recorded in the 1440 tax documentation for Cambridge, one is listed as 'Dutch', one is listed as 'Portuguese', and both are listed as servants. This suggests that alien women were much less likely to migrate to Cambridge for (documented) work reasons. It also highlights the limitations of the records, as it is likely that many more immigrant women were present but were not documented due to their marriage status.

Nationality	Number of Alien Females with Nationality	% Alien Population in 1440 (n=67)	Number of Alien Males with Nationality	% Alien Population in 1440 (n=67)
Brabanter	0		1	1.5%
'Dutch'	1	1.5%	43	64.2%
Fleming	0		1	1.5%
French	0		4	6.0%
Gascon	0		1	1.5%
Irish	0		6	9.0%
Picard	0		1	1.5%
Portuguese	1	1.5%	0	
Scott	0		3	4.5%
Swedish	0		1	1.5%
TOTAL	**2**	**3.0%**	**65**	**97.0%**

Table 3: Nationalities and sex of individuals assessed for the alien subsidy in 1440 in Cambridge (England's Immigrants 1330-1550, version 1.0 2020)

2.4.2.2 Scholars in Cambridge

Historical biographical records from Cambridge University can be used to make general assessments of the geographical origins of the alumni in the High/Late Medieval period (Aston 1980). The alumni were overwhelmingly English throughout this period, although there were fluctuations in the geographical areas that the University recruited from. In the 14th century, 56% of the recorded alumni were from dioceses in Eastern England, predominantly the dioceses of Norwich (39%) and Ely (11%). A further 20% were from the diocese of Lincoln and 13% were from the diocese of York. In the 15th century, non-collegiate records show a dominance of people from the Northern dioceses (39%), with 30% of the recorded alumni being from the diocese of York. Eastern dioceses formed 25% and 15% were recorded from the diocese of Lincoln. Colleges were influenced by individual preferences for recruitment but overall, the records for colleges indicate that most alumni were from Eastern dioceses (33%), followed by the Northern (25%) and Southern (11%) dioceses. Throughout the High/Late Medieval period, very few alumni were originated from outside of England. Only 1% of alumni were recorded as being from Wales, Scotland or Ireland. Similarly, only 1% were recorded as originating from outside of the UK altogether. Most of these were Friars studying Theology. In contrast to the records from the alien subsidies, very few of the continental European alumni were from the Low Countries - the majority were from Italy, Germany or Iberia. Clearly, there were inter-college differences, as well as differences between collegiate and non-collegiate institutions in the demographics within the University. Generally, the Eastern dioceses remained an important recruitment area for scholars but there were changes through time, with

the number of alumni from the Northern dioceses, particularly York, increasing in the 15th century.

2.4.3 Social Groups

The reasons and means for travel and migration in the High/Late Medieval period would have varied based on many social factors. Travel and migration happened across the social strata, but its nature may have been different – those who regularly travelled were generally in high-status roles – clergy, royal and governmental officials etc. Those in monastic orders and scholars also had the ability to be greatly travelled. These social groups overlapped - being well travelled and well educated went hand-in-hand and became part of the elite identity (Rubin 2006). There were vast differences in the status of aliens – from wealthy merchants, to skilled craftworkers, to those who worked in service (Ormrod *et al.* 2019). Travel and migration differed between sexes but even this was intersectional – with differing experiences depending on marriage status or where they migrated from (Lambert 2020). As much of the isotope analysis to date has been very small scale, few sites have been able to compare social groups within the High/Late Medieval period, although a study of the East Smithfield Black Death cemetery, an urban population with a catastrophic death profile, showed equal numbers of male and female non-locals.

2.4.4 Summary of Mobility in Cambridge

The combination of Cambridge as a trade hub and a centre of learning, with good transport links and frequent construction projects means that it was a prime location for population mobility, with transient merchants, traders and labourers, semi-transient scholars and permanent migrants, as well as emigrants (Darby 1977, Aston 1980, Ormrod *et al.* 2019, 2020). Historical evidence suggests that travel and migration was highly dependent on social factors and certain social groups were more likely to be mobile. Migration patterns changed through the High/Late Medieval period and were influenced by the Black Death. Isotope evidence to date is limited but has identified non-locals at High/Late Medieval sites.

2.5 Summary of Cambridge in Context

This chapter has placed Cambridge and its environs in the context of historical, archaeological and isotopic research regarding the history and development of the town and its environs, the pertinent transformative events that occurred in the High/Late Medieval period, as well as evidence for diet, travel and migration. While historical and archaeological evidence is plentiful for some aspects, it is patchy or non-existent for others. Archaeobotanical and zooarchaeological evidence are limited on provided information about individual consumption patterns, while historical data is incomplete or biased towards certain social groups. It is clear that isotope analysis can provide unique insights, particularly on an individual scale, but also on a population scale and would be suited to answer questions relating to social differentiation and sex. Reviews of current isotopic work in High/Late Medieval England agree that isotope analysis has great potential to add to our understanding of life in this period and much more research should be done (Woolgar *et al.* 2006, Müldner 2009, Jobling and Millard 2020).



3. Principles of Isotope Analysis in Archaeology

This chapter will discuss the principles underpinning carbon, nitrogen, oxygen and strontium isotope analysis in archaeological research, outlining their bio/geochemistry, as well as their use in archaeology and key limitations that should be considered.

3.1 What are Isotopes?

Isotopes of an element have the same number of protons in their nucleus but different numbers of neutrons, resulting in different atomic weights (Pollard *et al.* 2007). Light elements have few isotopes: carbon and nitrogen have two naturally occurring stable isotopes and oxygen has three. The isotope with the smaller atomic mass is usually more naturally abundant but the relative abundance can be altered through various biological and chemical processes, known as fractionation (*ibid.*). Heavy elements such as strontium behave slightly differently – they have several stable isotopes but can also have radioactively unstable isotopes. For these elements, it is primarily radioactive decay and subsequent geological processes that cause differences in abundance. It is this alteration in the abundance of isotopes of specific elements through known processes that forms the foundation of most isotope analysis in archaeological research.

3.1.1 Reporting Isotope Ratios

Isotope values for stable light isotopes are denoted using the delta symbol, 'δ', indicating the ratio of one isotope to another, relative to an international standard (Pollard *et al.* 2007). These

are reported as 'per mil' values, using the symbol '‰'. This is calculated using the following equation:

$$\delta_{sample}(‰) = \left(\frac{R_{sample} - R_{standard}}{R_{standard}}\right) \times 1000$$

Isotope values for strontium are reported as an absolute ratio between ^{87}Sr and ^{86}Sr.

3.2 Tissues for Archaeological Sampling

Isotope analysis in archaeology is based on the principle that the ratio of isotopes incorporated in human tissues during life is preserved after death in a largely unaltered, consistent manner that allows for estimations of diet, mobility, climate etc. to be made from the resulting isotope values.

Isotope analysis can be carried out on various biological tissues, including hair, nails, blood etc. but in archaeological studies, this is usually limited to bone and teeth, except in exceptional preservation circumstances. Diagenesis (physical and chemical alteration after deposition) and contamination can affect archaeological material and must be considered during isotope analysis of archaeological material (see Kendall *et al.* 2018). Relatively robust methods of assessing the quality of results and potential indicators of diagenesis and contamination have been developed for carbon and nitrogen isotope analysis (DeNiro 1985, Ambrose 1990) and various pre-treatment methods have been developed for oxygen (Koch *et al.* 1997, Grimes and Pellegrini 2013, Pellegrini and Snoeck 2016) and strontium isotope analysis (Hoppe *et al.* 2003) to try and mitigate the effects of diagenesis and contaminants.

Bone, dentine and tooth enamel are all organic/mineral composite materials, although they differ in structure and composition. The organic portion comprises predominantly of collagen, contained within a complex inorganic matrix of bioapatite, with bone collagen being 70% inorganic and 22% organic by weight and mature enamel being >96% inorganic by weight (Brudevold and Soremark 1967, Rowles 1967, Williams and Elliot 1989, Hillson 1996). Collagen is the preferred material for carbon and nitrogen isotope analysis in archaeology as it is abundant, relatively easy to isolate, survives quite well in the archaeological record and has been shown to reflect the isotopic composition of diet (DeNiro and Epstein 1978, 1981, Collins *et al.*

2002). The biological relationship between ingested sources of $\delta^{18}O$ and resultant oxygen isotope ratios in collagen is complex (e.g. Tuross *et al.* 2008). Therefore bioapatite is preferred for studies of oxygen isotopes in archaeology, as its isotopic signature has been shown to correlate with ingested water (Longinelli 1984, Luz, Kolodny, and Horowitz 1984, Luz, Kolodny, and Kovach 1984). Similarly, bioapatite is also the preferred material for strontium isotope analysis (Budd *et al.* 2000). The non-porous, majority inorganic structure of enamel is most resistant to diagenetic isotopic alteration, therefore making it a reliable material for oxygen and strontium, as well as carbon, isotope analysis (Budd *et al.* 2000, Hoppe *et al.* 2003, Zazzo *et al.* 2004)

Most biological tissues are resorbed and replaced throughout life meaning they are not 'static' records of isotopic signatures (Sealy *et al.* 1995). This 'turnover' rate can vary depending on the metabolic activity of the tissue (Thompson and Ballou 1956, Libby *et al.* 1964, Tieszen *et al.* 1983). There is still uncertainty regarding intra-tissue turnover, particularly bone collagen, with variable evidence that dense cortical bone, e.g. occipital, generally remodels slower than spongy cancellous bone, e.g. ribs (Fahy *et al.* 2017). Nuclear bomb testing in the 1960s caused a temporary spike in ^{14}C in the atmosphere, which can be detected in bone synthesised at the time (Stenhouse and Baxter 1979). The subsequent decrease in the ^{14}C measured in the bone of those who lived through the 1960s can be used to estimate actual, rather than relative, bone turnover. Hedges *et al.* (2007) measured ^{14}C in adult femoral mid-shaft sections and found that turnover was much higher in adolescence (10-30%/yr) and then decreased with age, with males showing slower turnover rates than females after 20yr. The isotope values of collagen in the femoral mid-shaft were shown to reflect an average ratio of well over 10yr of an individual's life (Hedges *et al.* 2007, p. 815). Tooth enamel and primary dentine do not remodel (Gage *et al.* 1989). This lack of tissue turnover therefore preserves the isotopic signature at the time of tooth formation, providing a chronologically restricted signal spanning from infancy to late adolescence/early adulthood, depending on the tooth sampled. Consequently, isotopic 'life histories' of individuals can be constructed by comparing results from tissues that turnover slowly to those that turnover more quickly, or not at all (Sealy *et al.* 1995).

3.2.1 Suitable Tissues

The available archaeological material from Cambridgeshire almost exclusively comprises of dry bone and teeth therefore sampling is restricted to suitable collagen and bioapatite samples from these tissues. A 'life history' approach (Sealy *et al.* 1995) involving sampling multiple tissues is the most appropriate to answer questions regarding individual and group experiences of life in High/Late Medieval Cambridge.

3.3 Carbon and Nitrogen Isotope Analysis

3.3.1 Principles of Carbon Isotope Analysis in Archaeology

Carbon has two naturally occurring stable light isotopes: ^{12}C (98.9 %) and ^{13}C (1.1%) (Pollard *et al.* 2007, p. 178). Carbon isotope values are reported relative to Vienna Pee Dee Belemnite (VPDB) on an internationally defined scale, where $^{13}C/^{12}C$ of NBS 19 carbonate is 1.00195 times that of VPDB (IAEA 1993).

Photosynthesis in plants (i.e. primary producers) is the principal source of carbon fractionation in food webs. The $\delta^{13}C$ signature of various plants is dependent on several factors during photosynthesis including the species-specific metabolic pathway of the plant and the isotope composition of the atmosphere (Pollard *et al.* 2007, p. 172). While atmospheric $\delta^{13}C$ in the past is taken to be between -6.4‰ and -7.0‰, values are variable by latitude and environment and can change through time (O'Leary 1981).

The two major plant types discussed in archaeological studies are termed 'C_3' or 'C_4'. This is based on their different photosynthetic pathways, which determine how each type discriminates against ^{13}C during carboxylation (Smith and Epstein 1971). In C_3 plants there is strong discrimination against ^{13}C by ribulose biphosphate carboxylase (Rubisco), whereas in C_4 plants phosphoenolpyruvate (PEP) carboxylase prevents further fractionation by Rubisco, resulting in less discrimination against ^{13}C (Farquhar *et al.* 1989). This process results in less negative $\delta^{13}C$ values in C_4 plants than C_3. Estimates vary based on plant type, environment, climate etc., but typically, the range in $\delta^{13}C$ values for C_3 plants is large (~-19.0‰ to -38.0‰), with a global mean of c.26.5‰ (O'Leary 1981, van der Merwe 1991, Pollard *et al.* 2007, Lee-Thorp 2008). The range in $\delta^{13}C$ values for C_4 plants is much smaller (~-6.0 to -15.0‰), with a global mean of

12.5‰ (O'Leary 1981, van der Merwe 1991, Pollard *et al.* 2007, Lee-Thorp 2008). This difference in the $\delta^{13}C$ values is used to discriminate isotopically whether a plant is C_3 or C_4 and used to interpret subsequent implications on food webs, although the ranges are large and may overlap in extreme cases (Tieszen 1991). This can be further complicated by the 'canopy effect', where ^{13}C becomes depleted in forests due to the recycling of ^{13}C-depleted CO_2 from soil respiration (van der Merwe and Medina 1991). This leads to more negative $\delta^{13}C$ values, particularly in areas of dense forestation, with values up to -37.0‰ being recorded in undergrowth leaves in the Amazonian forest (Medina *et al.* 1980). As forests are primarily C_3, and these depleted values affect the dependent food chains, this can complicate interpretations of C_3 vs C_4 diets (van der Merwe and Medina 1991). Aquatic plants exhibit wider ranges in $\delta^{13}C$ values than terrestrial plants due to the variation in available carbon sources, as well as fractionation factors such as pH, temperature and season (Zohary *et al.* 1994, Katzenberg and Weber 1999). The $\delta^{13}C$ values of marine and freshwater plants tend to be distinct as the $\delta^{13}C$ values of bicarbonate in marine water is generally 7.0 to 8.0‰ greater than atmospheric CO_2 (Smith and Epstein 1971), leading to marine plants having less negative $\delta^{13}C$ values.

Most global plant species (including aquatic plants) are C_3. Important edible C_3 plants include wheat, barley, oats, rye and rice. A much smaller proportion are C_4 and the majority of these comprise of subtropical grasses and sedges. Important edible C_4 plants include maize, sorghum and millet. Still *et al.* (2003) have produced a prediction model for modern distributions of C_3 and C_4 plants across the globe (Figure 5), estimating the total global coverage of C_3 plants at 87.4 million km^2 and C_4 plants at 18.8 million km^2. C_4 plants are adapted for aridity so the fraction of C_4 plants is greater towards the equator and in the southern hemisphere, with a very small fraction in the northern hemisphere and <0.005 in the UK.

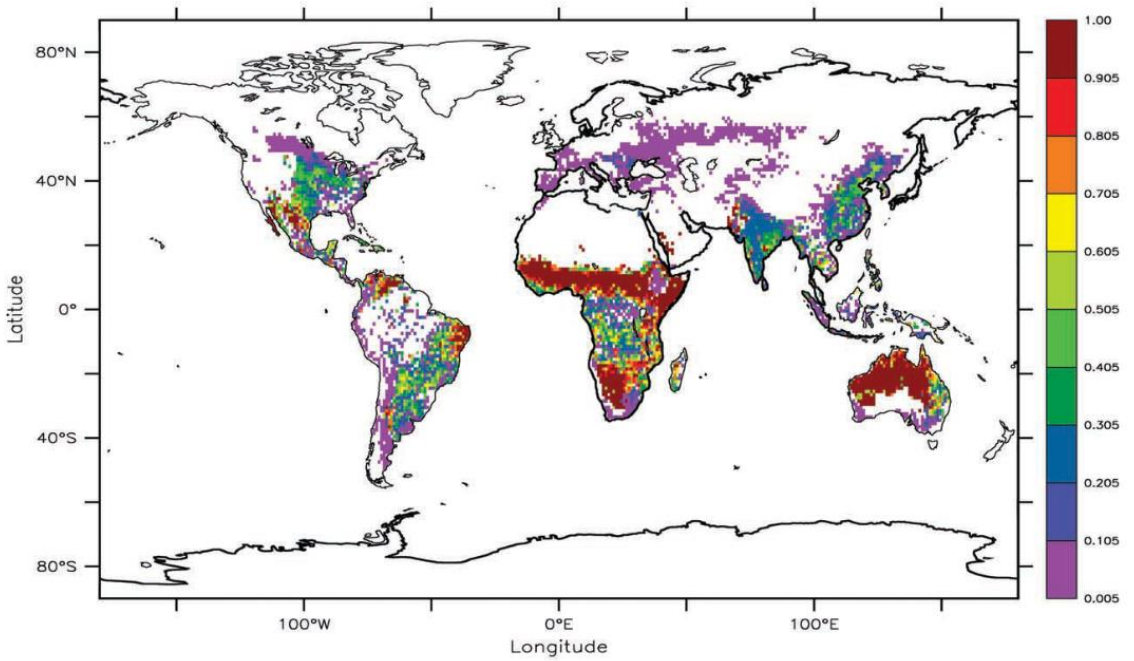


Figure 5: Map showing the approximate fraction of modern global vegetation that is C_4 (values below 0.005 are screened out) (Still et al., 2003, p. 7)

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Controlled animal feeding studies by DeNiro and Epstein (1978) showed that the carbon isotope signature of an animal reflects the carbon isotope signature of its diet, although there is variable enrichment depending on the tissue analysed. Further research proved a small, but significant trophic level effect, with $\delta^{13}C$ values becoming more positive by position in the food chain (e.g. Rau *et al.* 1983). Building on research of ^{13}C isotope enrichment in tissues of predators and prey (van der Merwe 1989, Szepanski *et al.* 1999), a study of predator/prey relationships in the Bialowieza Forest, Poland, led to an estimate of ^{13}C enrichment of 0-2‰ in the collagen of predators compared to the collagen their main prey (Bocherens and Drucker 2003). The small trophic level effect of $\delta^{13}C$ is a limitation for studies of archaeological diets, as small differences (<1‰) between human and animal isotope values would not allow us to distinguish between a human diet on a similar trophic level to the food sources, i.e. herbivorous, or one at a higher trophic level, i.e. omnivorous. It does indicate that values of ≈2‰ are likely to indicate a trophic shift between humans and their primary animal protein 'prey'. If a human-faunal offset is calculated using herbivore data only, then $\Delta^{13}C$ values ≥2% could be indicative of diets including 'prey' of a higher trophic level, e.g. omnivorous pigs or chickens, or marine

food sources. Further early controlled animal feeding studies found differential fractionation between diet and different tissue types ($\Delta^{13}C_{diet\text{-}tissue}$) (Ambrose and Norr 1993, Tieszen and Fagre 1993). It has been interpreted that $\Delta^{13}C_{diet\text{-}tissue}$ differences derive from differential macronutrient routing, with the $\delta^{13}C$ values in collagen primarily reflecting contributions from dietary proteins and the $\delta^{13}C$ values in bioapatite primarily reflecting contributions from the whole diet (e.g. carbohydrates, fats *and* proteins) (Krueger and Sullivan 1984, Lee-Thorp *et al.* 1989, Ambrose and Norr 1993, Tieszen and Fagre 1993, Jim *et al.* 2004, Kusaka *et al.* 2015). Therefore, combining $\delta^{13}C$ results from both collagen and bioapatite, such as calculating $\Delta^{13}C_{bioapatite\text{-}collagen}$ values, has been used to elucidate more information regarding trophic level, C_3/C_4 plant contributions and proportions of terrestrial versus marine proteins in past diet (Lee-Thorp *et al.* 1989, Kellner and Schoeninger 2007, Clementz *et al.* 2009, Kusaka *et al.* 2015). However, $\Delta^{13}C_{diet\text{-}tissue}$ relationships are complex. Part of this routing is related to essential amino acid requirements and synthesis of non-essential amino acids (Jim *et al.* 2006, Webb *et al.* 2017). Amino-acid routing can differ depending on the composition of the diet - for collagen, direct routing of amino acids is more likely in high protein diets, whereas in low protein diets, there is less direct routing and more synthesis of non-essential amino acids, meaning tissue values are more likely to reflect whole diet $\delta^{13}C$ (Jim *et al.* 2006, Webb *et al.* 2017). The $\delta^{13}C$ values of individual amino acids within collagen are well correlated with the $\delta^{13}C$ values of the bulk collagen and therefore routing and synthesis of amino acids is an important causal factor of wide variation in $\Delta^{13}C_{diet\text{-}collagen}$ values (Howland *et al.* 2003). $\Delta^{13}C_{diet\text{-}tissue}$ relationships have been shown to be significantly affected by an increased proportion of marine protein in the diet, potentially related to preferential routing of non-essential amino acids that are particularly abundant in marine food sources (Webb *et al.* 2017). Much is still unknown about dietary routing and factors which affect $\Delta^{13}C_{diet\text{-}tissue}$ and subsequent $\Delta^{13}C_{bioapatite\text{-}collagen}$ values, ultimately complicating the use of $\delta^{13}C$ values for interpretations of past diet, particularly when the diets are likely to be highly mixed and contain unknown quantities of marine proteins (Hedges 2004, Jim *et al.* 2006, Webb *et al.* 2017).

$\delta^{13}C$ values of marine fauna tend to be distinct from freshwater fauna due to the isotopic differences between marine and freshwater plants (Katzenberg and Weber 1999). Comparisons of archaeological freshwater, brackish and marine fish in Belgium found that freshwater fish had $\delta^{13}C$ values between -28.2‰ to -20.2‰, while the marine fish had values between -15.4‰

and -13.0‰ (Fuller *et al.* 2012). However, aquatic isotope values can vary considerably between bodies of water, even within the same species (Dufour *et al.* 1999). The use of seaweed as a fodder crop for terrestrial herbivores can also have an impact on subsequent $\delta^{13}C$ values in the terrestrial food chain. Sheep eating a diet containing seaweed have been shown to have much less negative $\delta^{13}C$ values, akin to values expected in a marine ecosystem (Balasse *et al.* 2005, 2009, Blanz *et al.* 2020).

Ultimately, for archaeology, $\delta^{13}C$ in human tissues will reflect the carbon isotope signature of their diet, with tissue-specific routing and minimal trophic level effect. $\delta^{13}C$ values from human tissue should be able to help determine whether an individual was eating a diet predominantly based on either C_3 or C_4 plants and whether marine resources were utilised.

3.3.2 Principles of Nitrogen Isotope Analysis in Archaeology

Nitrogen has two naturally occurring stable light isotopes: ^{14}N (99.6%) and ^{15}N (0.4%) (Pollard *et al.* 2007, p. 178). Nitrogen $\delta^{15}N$ values are reported relative to atmospheric nitrogen (AIR) (IAEA 1993).

Variation in nitrogen isotope abundance in biological materials is the result of complex nitrogen cycling in the natural environment, causing either depletion or enrichment through physical, chemical or biological processes (Högberg 1997, Handley *et al.* 1999, Robinson 2001). Fixation by microbial activity is the principal pathway through which nitrogen is made available in soils (Hoering and Ford 1960, Högberg 1997, Robinson 2001). The source of nitrogen a plant utilises is the primary driver of fractionation. Most plants either obtain nitrogen from ammonium and nitrates in soils or through a symbiotic relationship with microbes to fix atmospheric nitrogen (Kohl and Shearer 1980, Shearer and Kohl 1987, Robinson 2001, Szpak 2014). Climate, mycorrhizal fungi in the soil and nitrogen availability can also affect fractionation (Handley *et al.* 1999, Evans 2001, Robinson 2001, Amundson *et al.* 2003, Craine *et al.* 2009, Hobbie and Ouimette 2009).

DeNiro and Epstein (1981) carried out controlled feeding studies to prove the principle that the nitrogen isotope composition of an animal reflects the nitrogen isotope composition of its diet, although the resultant enrichment depends on the tissue analysed. Further diet studies by Minagawa and Wada (1984) demonstrated a stepwise enrichment of ^{15}N correlating with trophic

level (average 3.4 ±1.1‰), which appeared to be present regardless of habitat or species, ultimately meaning that herbivores, omnivores and carnivores can be distinguished by their $\delta^{15}N$ values. Subsequent studies of modern human tissues have shown that higher animal protein consumption results in higher $\delta^{15}N$ values (O'Connell and Hedges 1999, Bol and Pflieger 2002, Petzke *et al.* 2005). As aquatic food chains tend to have more trophic levels, aquatic fauna have the potential for higher $\delta^{15}N$ values than terrestrial fauna (Schoeninger and DeNiro 1984). Analysis of archaeological freshwater, brackish and marine fish by Fuller *et al.* (2012) found a large $\delta^{15}N$ range of 7.2-16.7‰ reflecting the numerous trophic levels. When coupled with the higher $\delta^{13}C$ values seen in marine fauna (see above), diets containing marine foods are generally isotopically distinct, as has also been shown in modern human dietary studies (Kuhnle *et al.* 2013, Patel *et al.* 2014). Freshwater fauna are generally not isotopically distinct from terrestrial food sources using $\delta^{15}N$ (and $\delta^{13}C$) values alone (Fischer *et al.* 2007, Hedges and Reynard 2007, Privat *et al.* 2007). Diadromous fish, e.g. eels, move between marine and freshwater environments and have been shown to have wide-ranging $\delta^{13}C$ and $\delta^{15}N$ values dependent on their life stage (Harrod *et al.* 2005, Fuller *et al.* 2012).

Predator/prey studies by Bocherens and Drucker (2003) indicate a range of 3.0‰ to 5.0‰ ^{15}N enrichment in predator collagen over the collagen of their prey, demonstrating the 'trophic level effect'. This value of 3.0-5.0‰ has generally been used to study trophic level, and by proxy, dietary habits, in humans but quantifying human $\Delta^{15}N_{diet\text{-}collagen}$ enrichment has been understudied and is particularly hindered by the complexities of human dietary habits (compared to other species studied), and human physiology (Hedges and Reynard 2007). For example, nitrogen isotope discrimination ($\Delta^{15}N_{diet\text{-}tissue}$) varies by species and is not constant for all protein types, with values depending on both protein quantity and quality (Robbins *et al.* 2005, 2010, Caut *et al.* 2009, Florin *et al.* 2011). The protein quality of a food source can be estimated based on its amino acid profile and how well these amino acids are then absorbed and retained in the consumer, with a 'high-quality' protein sources, such as milk, fish and meat, ultimately being a good match to the consumers dietary requirements (Florin *et al.* 2011). Studies of animals indicate that $\Delta^{15}N_{diet\text{-}tissue}$ decreases with increased high-quality protein consumption (Robbins *et al.* 2005) but this correlation can be complicated by mixed diets (Robbins *et al.* 2010, Florin *et al.* 2011). However, determining $\Delta^{15}N_{diet\text{-}tissue}$ requires species-specific systematic feeding experiments which test the isotopic values of the food sources *and*

the consumer tissues (McLaren *et al.* 2015). The first controlled dietary study of human diet-body isotope enrichment was carried out by O'Connell *et al.* (2012) and found the $\Delta^{15}N_{diet\text{-}red\ blood\ cell}$ was +3.5‰ in modern individuals following a habitual mixed omnivorous diet, resulting in an increased estimate of the $\Delta^{15}N_{diet\text{-}collagen}$ of ≈+6.0‰. This human-specific $\Delta^{15}N_{diet\text{-}tissue}$ value should be considered alongside estimations by Bocherens and Drucker (2003) when estimating animal protein consumption. However, while considering protein quality as well as quantity is important for archaeological interpretations, there are still many unknowns in determining diet in the past, particularly regarding the type, quantity, quality and importantly, isotopic value of the proteins consumed. Despite attempts to quantify archaeological diet in more detail (e.g. using stable isotope mixing models (Cheung and Szpak 2020)), these unknowns are often insurmountable and/or the assumptions that have to be made render the results too ambiguous (e.g. Richards *et al.* 2006). This therefore means that, often, interpretations of diet in past from $\delta^{15}N$ values are largely limited to general inferences regarding trophic level (Cheung and Szpak 2021).

The application of fertilisers to soils can affect $\delta^{15}N$ values in crops. The practice of manuring with ^{15}N-rich animal dung has been shown to increase cereal and legume $\delta^{15}N$ values, sometimes to the equivalent of a trophic level effect (e.g. Bogaard *et al.* 2007, Fraser *et al.* 2011, Kanstrup *et al.* 2011, Treasure *et al.* 2016). Other fertilisers, such as seaweed, have also been shown to induce an increase in $\delta^{15}N$ values in treated crops (Blanz *et al.* 2019). These high $\delta^{15}N$ values affect subsequent consumers in the food chain, leading to considerable implications for the interpretation of $\delta^{15}N$ values in human consumers.

Fractionation of nitrogen isotopes can be affected by factors which affect the homeostasis of an organism, resulting in catabolism or anabolism (Schoeller 1999, Fuller *et al.* 2005). In humans, this could be caused by events such as starvation, disease or pregnancy, which can have implications for the interpretation of archaeological isotope data. It has been demonstrated that acute nutritional stress affects $\delta^{15}N$ values in animals (Hobson *et al.* 1993, Cherel *et al.* 2005, Robertson *et al.* 2014). Studies of humans suffering from periods of nutritional stress, such as extreme morning sickness in pregnancy (Fuller *et al.* 2005), anorexia nervosa (Mekota *et al.* 2006) or even those who have undergone bariatric surgery (Canterbury *et al.* 2020), demonstrate elevated $\delta^{15}N$ values in bodily tissues, with extreme cases leading to a trophic level effect. This

elevation is due to metabolic and physiological changes involving a negative nitrogen balance and catabolism of proteins within the body (Hughes *et al.* 2018). The inducement of a catabolic state is an important factor to consider when interpreting nitrogen isotope values in archaeology as there is a chance that an individual with high $\delta^{15}N$ values could, counterproductively, be the result of a high/marine protein diet *or* the result of prolonged nutritional stress/wasting.

Pregnancy has also been shown to have an effect on isotope values in the tissues of the mother (Fuller *et al.* 2005). Pregnancy should induce an anabolic state with positive nitrogen balance (*ibid.*). Analysis of $\delta^{15}N$ values in the hair of pregnant women by Fuller *et al.* (2005) showed a significant decrease of -0.3 to -1.1‰ from pre-pregnancy to birth, a pattern which prevailed despite dietary differences. This is another complication to consider when interpreting isotope values in archaeology, as, depending on the tissues analysed, this could result in lower $\delta^{15}N$ values in females who died close during, or soon after pregnancy, but these may not be distinguishable from females who had a diet containing low amounts of animal protein.

Tissues of infants (esp. 0-1yr) tend to have higher $\delta^{15}N$ values than adults (Reynard and Tuross 2015, p. 623). As infants are weaned onto non-milk foods, their $\delta^{15}N$ values tend to decrease until they are similar to adult $\delta^{15}N$ values (Reynard and Tuross 2015, p. 619). An early isotope study of modern breastfeeding mothers and nursing babies found that the fingernails from the babies were always enriched in ^{15}N compared to the mother and that this enrichment decreased as weaning began (Fogel *et al.* 1989). Early investigations into isotopic evidence of breastfeeding and weaning in the past concluded that this isotopic pattern could also be detected in archaeological non-adult bone collagen (e.g. Fogel *et al.* 1989, Katzenberg *et al.* 1993), with the predominant explanation for this being that consuming breastmilk effectively produces a trophic level effect in the infants (Fuller *et al.* 2006). Subsequently, many archaeological studies have tried to identify weaning in non-adult skeletal remains (see Mays *et al.* 2002, Richards *et al.* 2002, Fuller *et al.* 2003, Burt 2013 for examples from English Medieval sites). However, it has been argued that our current understanding of weaning and how to detect it is oversimplistic and that complex issues of tissue fractionation, bone turnover and infant physiology may complicate interpretations (Steele and Daniel 1978, Jenkins *et al.* 2001, Reynard and Tuross 2015).

$\delta^{15}N$ values can also be affected by various diseases and trauma. Katzenberg & Lovell (1999) and Olsen (2014) have measured intraskeletal $\delta^{13}C$ and $\delta^{15}N$ values in normal and pathological human bone and found changes related to bone-forming pathologies. Bone calluses at fracture sites, bone affected by non-specific infection (osteomyelitis) and non-specific inflammation (periostitis), as well as joints affected by osteoarthritis, all exhibited intraskeletal differences in their $\delta^{15}N$ values between observably pathological bone and non-pathological bone. Explanations vary based on aetiology but are based on the disruption of nitrogen balance as the body syntheses new bone or reacts to infection (Olsen *et al.* 2014). Diseases associated with loss of bone mass have also been shown to affect isotopic values. White and Armelagos (1997) demonstrated elevated $\delta^{15}N$ values in bone collagen from mummies with evidence for osteopenia, linking this to differential urea excretion and renal processing of calcium and phosphorus. Other diseases have been shown clinically to affect general physiology, causing a difference in $\delta^{15}N$ values (Reitsema 2013). For example, a study measuring the $\delta^{15}N$ values in the hair of modern individuals with end-stage liver disease (cirrhosis) found their $\delta^{15}N$ values to be 3.2‰ lower than healthy patients, linked to changes in protein and amino acid metabolism (Petzke *et al.* 2006). Overall, these studies indicate that observably pathological bone is unlikely to provide a good isotopic representation of diet and should be avoided in archaeological sampling for dietary studies and that while many other pathologies cannot be directly observed in archaeological skeletal evidence, their possible influence should be considered.

Ultimately, for archaeology, analysis of $\delta^{15}N$ values in human tissues reflect the nitrogen isotope signature of their diet, with tissue-specific routing and a trophic level effect. However, there may also be physiological and metabolic changes that influence the $\delta^{15}N$ values recorded. $\delta^{15}N$ values in human tissues should be able to indicate whether an individual was essentially herbivorous or omnivorous and whether marine resources were utilised.

3.3.3 Applying Principles of Carbon and Nitrogen Isotope Analysis to Medieval Cambridge

The sections above have outlined the principles behind carbon and nitrogen isotope analysis in archaeology. Carbon and nitrogen isotopes are extremely useful tools for providing information about diet, although it should be emphasised that the type of information gained is relatively crude and conclusions are not absolute. Many of the biological processes described are not yet fully understood, particularly regarding nitrogen fractionation, and all results should be considered in the context of potential unknown variation (Makarewicz and Sealy 2015). In particular, there is an increasing emphasis on the need to sample contemporary faunal and floral material to characterise the local environment and account for any potential variations in $\delta^{13}C$ and $\delta^{15}N$ values of primary producers and consumers that may have subsequent effects on human values (Makarewicz and Sealy 2015). Bownes *et al.* (2018) found substantial differences in $\delta^{13}C$ and $\delta^{15}N$ values between faunal material selected from two sites to provide faunal 'isotopic baselines' for High/Late Medieval human skeletons from Yorkshire, despite the sites being in proximity, with similar environments, geology and chronologies. The differences were attributed to natural or human influences on the plants utilised and/or soil isotope values and ultimately it was decided that this rendered the human isotopes from the two sites to be incomparable. The decision to rule out any possibility of comparison is perhaps extreme, but the paper does highlight the need to account for spatial and chronological changes in the food sources available to individuals in Cambridgeshire to as high a resolution as possible.

Figure 6 shows 'typical' human and faunal carbon and nitrogen isotope values for different ecosystems in Northwest Europe (Müldner 2009). Based on information about Medieval diet from Chapter 2, as well as previous isotope studies in High/Late Medieval Britain, we can make some predictions about the expected isotopic signature for Medieval Cambridge and where their values might plot.

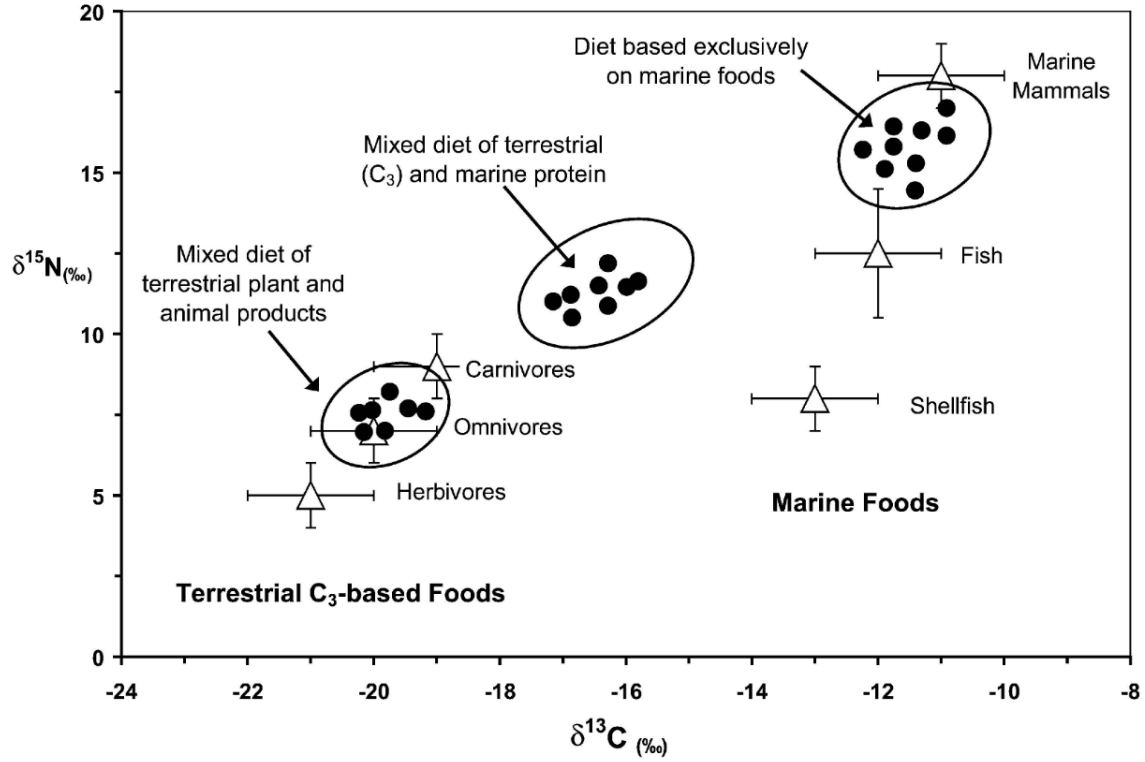


Figure 6: Scatterplot showing 'typical' $\delta^{13}C$ and $\delta^{15}N$ values for terrestrial and marine foodwebs in temperate Northwest Europe (Müldner 2009, p. 330). Circular symbols represent typical human bone collagen values for terrestrial C_3, mixed or marine-based diets (terrestrial C_4 not shown), triangular symbols represent typical terrestrial and marine bone collagen stable isotope values (±1SD)(after Richards (2000), Müldner, 2009)

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Based on the favoured growing areas of C_4 plants shown in Figure 5 (although it is based on modern data) and the fact that the vast majority of plants, including many of the important edible plants available in the Medieval period, are C_3, it would be expected that this will be reflected in the isotope values seen in Cambridge. Evidence of C_4 plants in isotope studies of British sites of any time period is rare, indeed, it is almost exclusively limited to two 2nd/3rd century individuals from Roman Driffield Terrace, York (Müldner *et al.* 2011) and a 3rd/4th century individual from Gravesend, Kent (Pollard, Ditchfield, *et al.* 2011), all of whom were found to have high $\delta^{13}C$ values. In continental Europe, C_4 isotopic signatures are more commonly identified in Medieval archaeological skeletons. They have been identified in 8th-13th century skeletons from Trino Vercelle, Northern Italy (Reitsema and Vercellotti 2012), 13th-16th century skeletons from Valencia, Spain (Alexander *et al.* 2015) and 13th-14th century skeletons

from Thebes, Greece (Dotsika *et al.* 2018). This is commonly attributed to consumption of millet, known to be grown in Europe (but not a staple crop in Britain) since the Neolithic period (Hunt *et al.* 2008). Therefore, if a C_4 isotopic signature is detected at Cambridge, this may be evidence of the import of edible C_4 products from outside of Britain or evidence of a person who has travelled from an area with greater access to C_4 products.

Based on information about Medieval diet (Chapter 2) and previous isotope studies, it is assumed that most High/Late Medieval individuals consumed some degree of animal protein and were therefore omnivores. This would incur a trophic level effect and would place them at least 3-6‰ above herbivores (Bocherens and Drucker 2003, O'Connell *et al.* 2012). It is likely that High/Late Medieval individuals had access to freshwater food sources, although, as discussed above, freshwater food sources are difficult to distinguish using carbon and nitrogen isotopes. It is also likely that at least some High/Late Medieval individuals had access to marine food sources and regular consumption of marine resources should be quite evident in the resulting high $\delta^{13}C$ and $\delta^{15}N$ values isotope values. Based on religious stipulations and the fish event horizon, leading to increased access to marine fish, variation in the evidence for marine consumption, demonstrated by large ranges in $\delta^{13}C$ and $\delta^{15}N$ values is predicted.

It is therefore expected that individuals from Cambridge will exhibit isotope values indicative of a mixed C_3 terrestrial/marine diet, causing them to plot between the C_3 and marine ecosystems in Figure 6. The likely largest cause for variation during this period will be the consumption of marine resources, probably causing a wide range of values. This has been observed at Late Medieval Fishergate, York, with the individuals forming a positively correlated linear scatter towards high $\delta^{13}C$ and $\delta^{15}N$ values (Müldner 2016) (Figure 7).

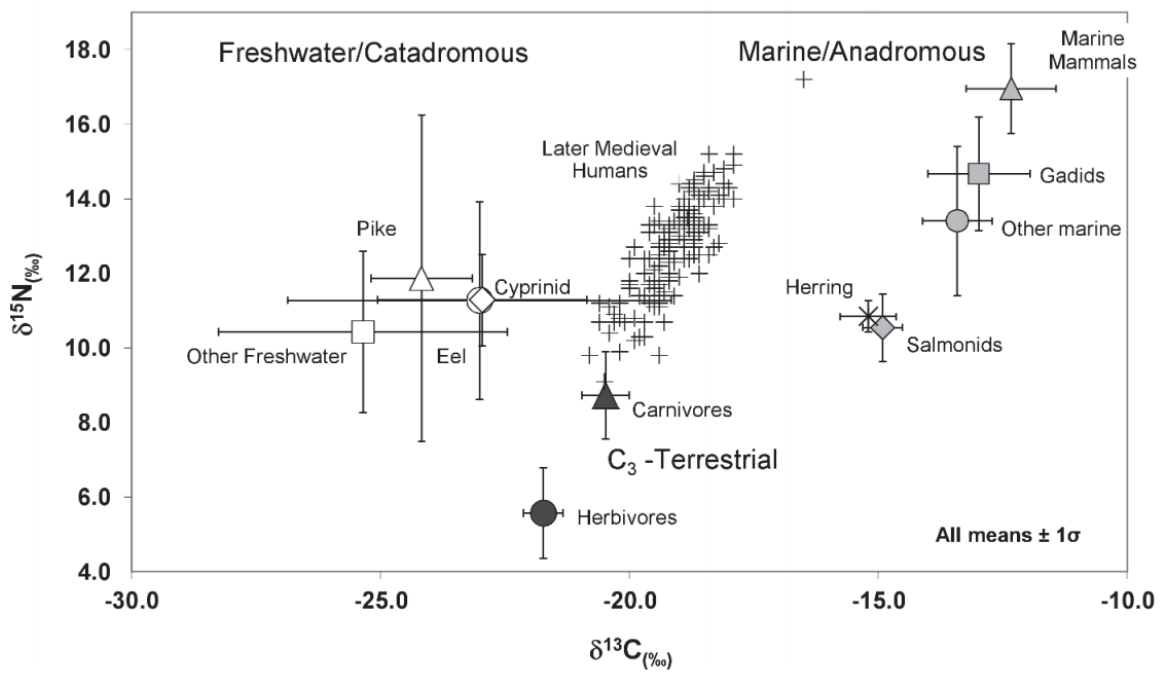


Figure 7: Human carbon and nitrogen isotope data from the Late Medieval Gilbertine Priory at Fishergate, York (13th-16th century) in context with faunal isotope values, showing the human diet was mixed, with some marine protein (Müldner, 2016, p. 240)

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Aside from the diet, the other factors which could affect $\delta^{13}C$ and $\delta^{15}N$ should be considered. The potential influence of acute nutritional stress should certainly be taken into account for isotope values obtained from individuals from Cambridge, particularly in light of the Great Famine (1315-1322) and other High/Late Medieval famine events (Alfani and Ó Gráda 2018) (Section 2.3.1.4). However, attempts to detect isotope changes related to famine in bulk rib and dentine collagen from High/Late Medieval individuals from St Mary Spital, London were undiagnostic, with dietary changes being indistinguishable from catabolic effects of starvation (Walter *et al.* 2020). This implies that Cambridgeshire individuals would have to have suffered from nutritional stress over a long enough period to leave a signature in the tissues analysed, and even then, the signatures may not be diagnostic. The depletive effect of pregnancy on $\delta^{15}N$ values in females from Cambridge should be considered, however, a study which attempted to evaluate the effect of parity status on $\delta^{15}N$ values in 18th and 19th-century skeletons from London found no detectable effect and concluded very specific conditions would have to be

present to prove the cause of the values (Nitsch *et al.* 2010). As this study is not primarily concerned with detecting weaning signals in Cambridgeshire, the main consideration will be to mitigate the weaning effect and ensure that either infants and young children are avoided for general sampling for dietary isotopes, or that their results are considered separately to the adult population.

3.4 Oxygen Isotope Analysis

3.4.1 Principles of Oxygen Isotope Analysis in Archaeology

Oxygen has three naturally occurring light stable isotopes: ^{16}O (99.76%), ^{18}O (0.2%) and ^{17}O (0.04%) (Pollard *et al.* 2007, p. 178). Oxygen values are reported on a scale either relative to Vienna Pee Dee Belemnite (VPDB) or relative to Vienna Standard Mean Ocean Water (VSMOW) and Standard Light Antarctic Precipitation (SLAP), where $^{18}O/^{16}O$ of SLAP is 0.9445 times that of VSMOW (IAEA 1993).

Differential condensation and evaporation throughout the water cycle is the principal driver of differences in oxygen isotope ratios for archaeological studies (see Pederzani and Britton (2019) for a comprehensive summary). The $\delta^{18}O$ signature of precipitation can be highly variable depending on environmental conditions (particularly temperature) and the $\delta^{18}O$ signature of the rainout depends on factors including altitude, latitude and distance from coastlines (Dansgaard 1964, Pederzani and Britton 2019). Consequently, $\delta^{18}O$ values in water are directly correlated to environmental conditions such as latitude/altitude, rainfall and air temperature (Figure 8).

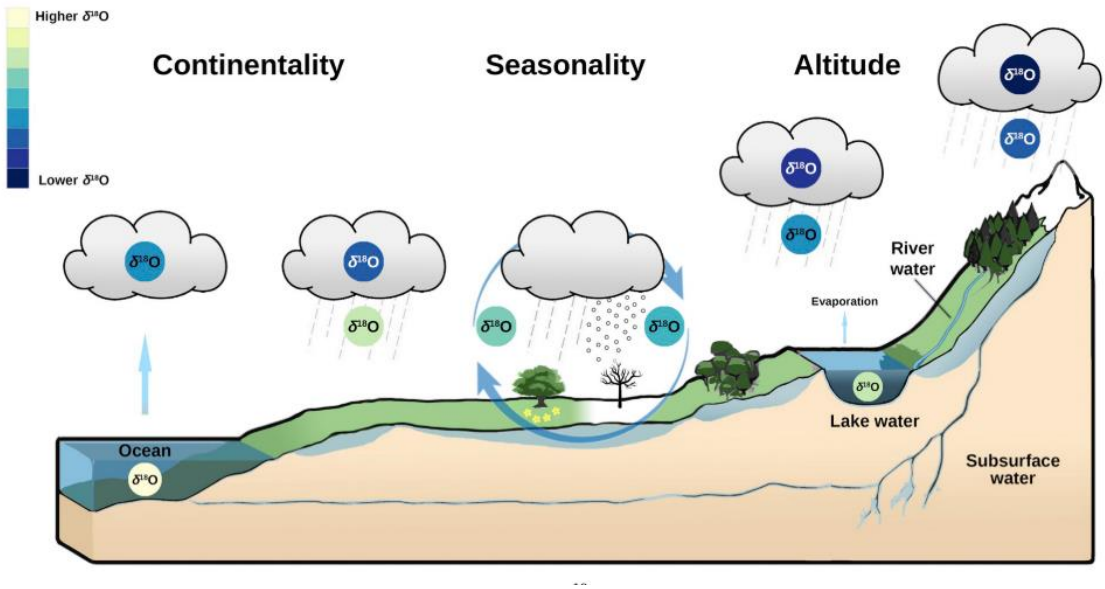


Figure 8: Effects of continentality, seasonality, altitude on $\delta^{18}O$ values in the water cycle (Pederzani and Britton, 2019, p. 79)

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Building on documented $\delta^{18}O$ values of meteoric precipitation by the International Atomic Energy Agency (IAEA) and World Meteorological Organization (WMO) (Rozanski *et al.* 2013), and previous models (see Bowen 2010a), complex statistical and geostatistical modelling of the global-scale distribution in $\delta^{18}O$ isotope values has been carried out by Bowen and colleagues (Bowen and Wilkinson 2002, Bowen and Revenaugh 2003, Bowen 2008, 2010b). Figure 9 shows global models of precipitation $\delta^{18}O$, highlighting the correlation with latitude, elevation and coastlines (Bowen 2010b). The maps also highlight the relative homogeneity and lack of inter-annual change across large areas, including northern Europe.

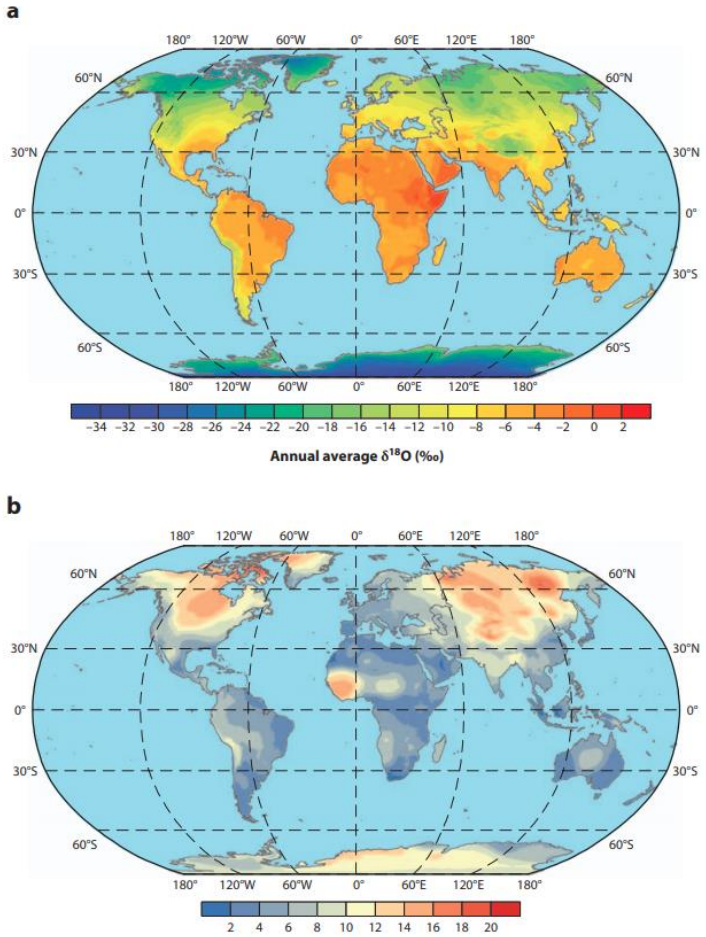


Figure 9: Models of global $\delta^{18}O$ values of precipitation. '(a) Long-term, precipitation-amount weighted annual average $\delta^{18}O$ values of precipitation, estimated using data from the Global Network of Isotopes in Precipitation and the literature and the method of Bowen & Revenaugh (2003). (b) Intra-annual range of precipitation $\delta^{18}O$ values; data from Bowen (2008)' (Bowen 2010b, p. 168)

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Comparisons of modern water samples from the British Isles suggest that overall, the oxygen isotope composition of groundwater is similar to precipitation and therefore the $\delta^{18}O$ values can generally be used interchangeably (Darling and Talbot 2003, Darling *et al.* 2003). Figure 10 shows a modern groundwater map for the British Isles, confirming that the values correlate to precipitation levels, as the Southwest receives the highest mean annual rainfall (Darling *et al.* 2003, Pellegrini *et al.* 2016). The range in groundwater $\delta^{18}O$ values for the British Isles is ~4.0‰ and the contours of the $\delta^{18}O$ groundwater map are very broad, meaning similar values characterise large areas.

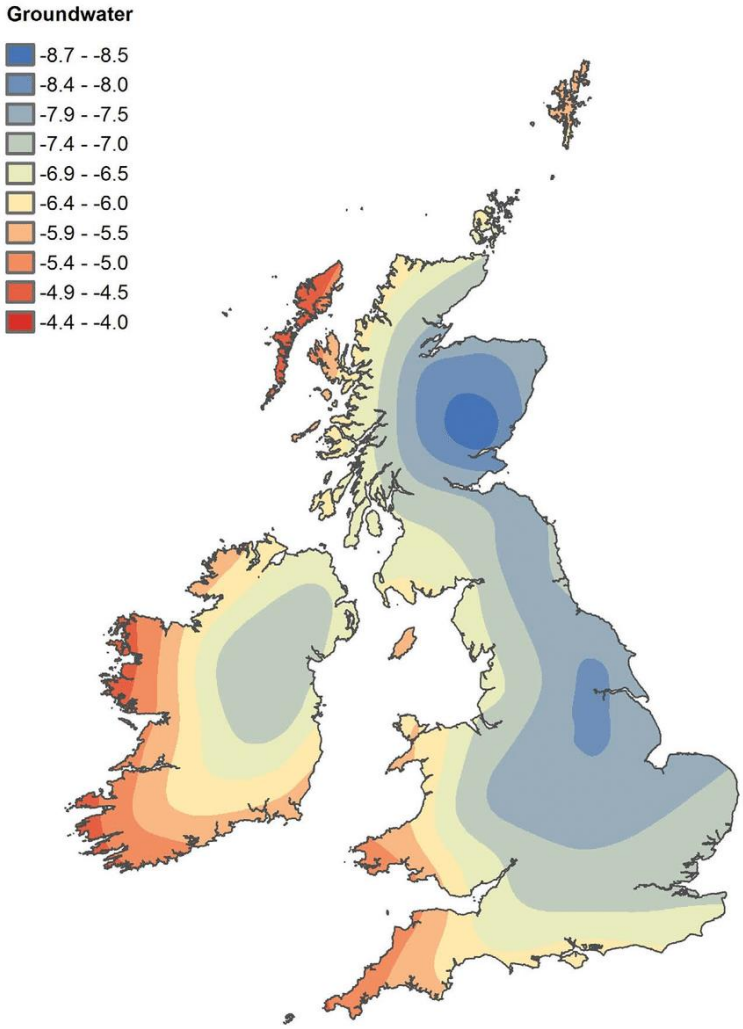


Figure 10: Modern groundwater $\delta^{18}O$ values for Britain and Ireland (Pellegrini et al., 2016, p.4), adapted from (Darling et al. 2003)

['Groundwater oxygen isotope ratio distribution values from Britain and Ireland, showing the decrease in $\delta^{18}O$ values from southwest to northeast (modified from Darling et al.)' in Pellegrini et al. 2016 is licenced under CC BY 4.0]

Bioapatite contains oxygen isotopes both in carbonate (CO_3^{2-}) and phosphate (PO_4^{3-}) forms (Wilson *et al.* 1999, Chenery *et al.* 2012). The isotope values obtained from these forms are not the same and they do not have the same values to the whole body water pool and so require further calculations in order to be used comparatively. A linear relationship between $\delta^{18}O$ values in human and animal bone phosphate ($\delta^{18}O_p$) and the $\delta^{18}O$ values in local meteoric water was determined by Longinelli (1984). Consequently, it was established that oxygen isotopes measured in bone are correlated with the isotopic composition of ingested water (mostly through consumption of liquids and food) and could, therefore, provide information about the climatic conditions in which the sampled organism lived (Longinelli 1984, Luz, Kolodny, and Horowitz 1984, Luz, Kolodny, and Kovach 1984). However, fractionation occurs within the body tissues and equations are required to convert the $\delta^{18}O_p$ values from bioapatite to values which can be compared to potential water sources ($\delta^{18}O_w$).

Daux *et al.* (2008) produced the following equations to convert tooth enamel phosphate $\delta^{18}O$ values:

> *Enamel phosphate to water conversion equation* ***4*** *(based on new data from Daux et al. only, using modern teeth from 12 sites, modern tap water samples, and the Online Isotopes in Precipitation Calculator (OPIC)):*
>
> $$\delta^{18}O_w = 1.73\ (\pm 0.21)\ \times\ \delta^{18}O_p\ -37.25\ (\pm\ 3.55)$$
>
> *Enamel phosphate to water conversion equation* ***6*** *(based on a combination of data from Daux et al., Longinelli (1984), Luz et al. (1984) and Levinson et al. (1987)):*
>
> $$\delta^{18}O_w = 1.54\ (\pm 0.09)\ \times\ \delta^{18}O_p\ -33.72\ (\pm\ 1.51)$$

Chenery *et al.* (2012) showed that $\delta^{18}O$ values measured in tooth enamel carbonate ($\delta^{18}O_c$) were a 'robust, rapid and cost-effective' alternative to analysing $\delta^{18}O_p$. They also established a constant relationship between $\delta^{18}O_p$ and $\delta^{18}O_c$ in human tooth enamel and produced equations to allow conversion of the different values, as well as a complementary calculation to Daux *et al.* (2008) to convert $\delta^{18}O_c$ to drinking water ($\delta^{18}O_{dw}$).

Chenery et al. (2012) carbonate to phosphate conversion equation (after using Coplen 1988 to convert $\delta^{18}O_C$ (VPDB) to $\delta^{18}O_C$ (VSMOW)):

$$\delta^{18}O_{p\,(VSMOW)} = 1.0322 \times \delta^{18}O_{c\,(VSMOW)} - 9.6849$$

*Chenery et al. (2012) carbonate to drinking water conversion equation, for Daux et al. equation **4**:*

$$\delta^{18}O_{dw} = 1.786 \times \delta^{18}O_{c\,(VSMOW)} - 54.005$$

*Chenery et al. (2012) carbonate to drinking water conversion equation, for Daux et al. equation **6**:*

$$\delta^{18}O_{dw} = 1.590 \times \delta^{18}O_{c\,(VSMOW)} - 48.634$$

For archaeological studies, there are several approaches to interpreting $\delta^{18}O$ values from human tissues (Pederzani and Britton 2019). One approach has been to compare the converted $\delta^{18}O$ values from tooth enamel to expected 'local' $\delta^{18}O$ water values to identify whether the values assimilated during tooth formation match the values for the region the individual was buried in and if not, this could indicate they migrated from elsewhere. This can be taken a step further with a provenancing approach, where comparisons to maps of $\delta^{18}O$ water values can then be used to identify potential regions that better match the values – a particularly well-known and high-resolution Late Medieval example being the multi-isotope analysis of Richard III (Lamb *et al.* 2014).

However, a provenancing approach is simplistic and it has been shown that the variation in $\delta^{18}O$ values within most archaeological populations is very large (>3.0‰). Therefore, due to the limited geographic variation (e.g. Figure 10), there is a large overlap in values from different regions (Lightfoot and O'Connell 2016). Due to the complexities of fractionation in human tissues, caution has also been raised in using converted values, particularly when performing multiple conversions to drinking water values, as errors may become large in some cases (Pollard, Pellegrini, *et al.* 2011). While conversion aids the comparison of enamel $\delta^{18}O$ values to maps of known water values, it is also recommended that, where possible, the unconverted values are also analysed (*ibid.*). Distribution maps constructed directly from archaeological $\delta^{18}O$ values can go some way to overcoming problems of conversion, allowing $\delta^{18}O$ values from tissues to be directly compared (Pellegrini *et al.* 2016). A comparison of mean and 1SD enamel $\delta^{18}O_p$ (VSMOW) values from 'local' archaeological populations from Britain and Ireland

showed the values roughly fell into two biogeographic groups approximately aligned with East/West low/high rainfall areas (Evans *et al.* 2012).

The British Geological Survey (BGS) Biosphere Isotope Domain GB Map (Figure 11) combines these groups with contours from Darling *et al.* (2003), showing the majority of Britain falls within the green contour (16.6‰ to 17.9‰). While more directly comparable for archaeological isotope values, the division into only two groups has limited usefulness for archaeological comparisons. Indeed, due to the poor resolution and overlap in the data, Lightfoot and O'Connell (2016) caution against using $\delta^{18}O$ values to identify specific 'homelands' and instead recommend a statistical approach to identify population-specific $\delta^{18}O$ outliers.

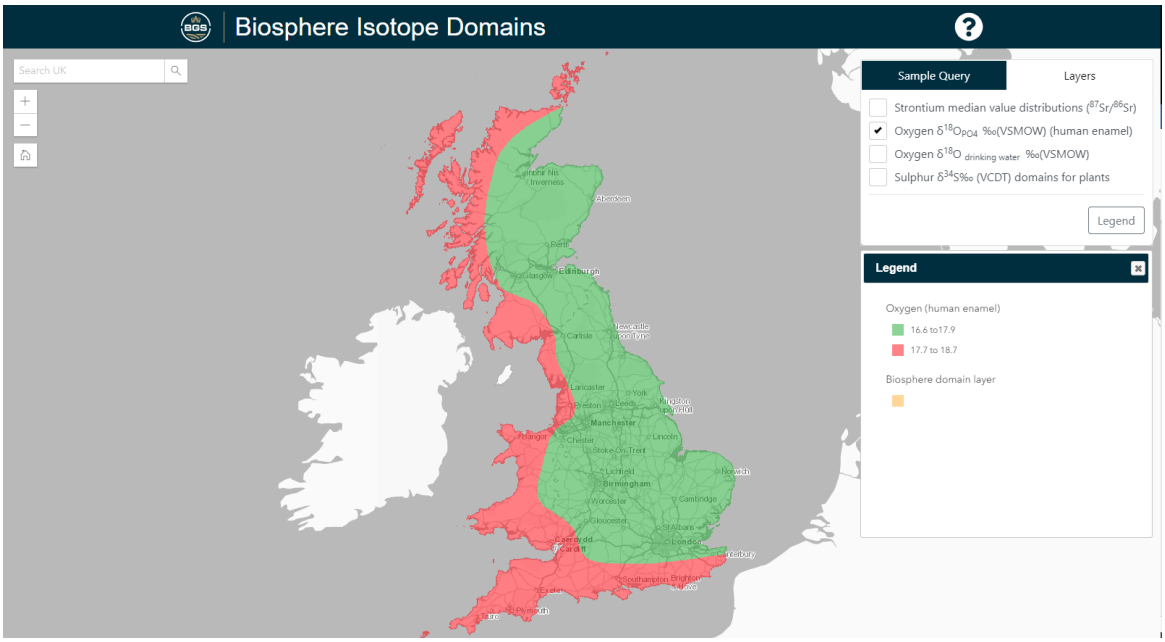


Figure 11: The British Geological Survey Biosphere Isotope Domain GB Online Map showing the layer for $\delta^{18}O$ PO4 ‰ (VSMOW), estimated from oxygen isotope variations in tooth enamel given as the mean and 1SD of 'local' populations (Evans, Chenery, et al., 2018)

[Created using the Biosphere Isotope Domains GB (V1): Interactive Website, British Geological Survey © UKRI 2021. All rights reserved, contains OS Open Data]

As $\delta^{18}O$ values are related to climate, it should be remembered that short-term climatic fluctuations in the past could also have affected $\delta^{18}O$ values, complicating longue durée studies (Pellegrini *et al.* 2016). Other issues that must be considered when interpreting $\delta^{18}O$ values from human tissues include the utilisation of different water sources and cultural modification to

ingested water. Cooking activities involving brewing, stewing and boiling of water can alter the $\delta^{18}O$ values through fractionation, with experiments showing the preparation of ale could result in a 1.3‰ increase over water and slow-cooked 'pottage' could result, on average, in an increase of 10.2‰ (Brettell *et al.* 2012). Further experiments involving differential cooking of meat and fish have shown that the type of flesh, as well as the type of cooking method, e.g. boiling or roasting, can have differential effects on a range of isotope values (Royer *et al.* 2017).

There may be evidence that severe pathologies can affect $\delta^{18}O$ values. Kuo *et al.* (2012) demonstrated low $\delta^{18}O$ values in human blood plasma in those with end-stage renal disease. Renal failure can be caused by many things including 'medications, diabetes mellitus, hypertension, sepsis, personal lifestyle' (Kuo *et al.* 2012, p. 7). Although these causes are either irrelevant or undetectable in archaeological skeletons, pathology is another factor to bear in mind when interpreting $\delta^{18}O$ values.

In summary, for archaeology, $\delta^{18}O$ values in human bioapatite will largely reflect the oxygen isotope signature of the water ingested at the time of tissue formation, with tissue-specific fractionation. The $\delta^{18}O$ values in human bioapatite should be an indicator of the environmental conditions governing the $\delta^{18}O$ values of the water ingested and can be used as a tool for identifying population outliers, 'non-locals' and even for provenancing. However, $\delta^{18}O$ values alone can be undiagnostic and should be interpreted with caution.

3.4.2 Applying Principles of Oxygen Isotope Analysis to Medieval Cambridge

The above section has outlined the principles behind oxygen isotope analysis in archaeology, predominantly its use as a tool for identifying population mobility and outliers. It is clear that oxygen isotope analysis provides useful information but there are severe limitations in its interpretation, particularly when used alone. Therefore, the application of oxygen isotopes to Cambridgeshire individuals should follow recommendations by Pederzani & Britton (2019) that $\delta^{18}O$ values are best considered in the context of a multi-isotope study and that limitations should always be acknowledged. The analysis of site-specific outliers, following Lightfoot and O'Connell (2016) would be a suitable strategy for identifying potential 'non-local' individuals in

High/Late Medieval Cambridge and over-reliance on converted values and attributions to 'homelands' based on $\delta^{18}O$ values alone will be avoided.

While we should always consider the concerns regarding conversion equations and complexities in fractionation, it is still worthwhile establishing what the Cambridgeshire $\delta^{18}O$ signature may be. Cambridge is located in Eastern Britain, c.75km+ from the coast. It has an extremely flat, low-lying landscape and has a relatively low mean annual rainfall of <700m (Darling and Talbot 2003). The Online Isotopes in Precipitation Calculator (OICP) estimated annual precipitation $\delta^{18}O$ value for Cambridge is -7.4‰ (Bowen 2015) and it straddles the boundary between -7.9 to -7.5‰ and -7.4 to -7.0‰ on the modern $\delta^{18}O$ groundwater map (Figure 10). Cambridge is within the area of the East biogeographic group on the BGS Biosphere Map (Figure 12). Based on Evans *et al.* (2012), the minimum and maximum oxygen isotopes values for Cambridge given on the BGS Biosphere map are: $\delta^{18}O_p$ (VSMOW) = 16.55‰ to 17.85‰, $\delta^{18}O_c$ (VSMOW) = 25.42‰ to 26.68‰, $\delta^{18}O_c$ (VPDB) = -5.28‰ to -4.06‰ and $\delta^{18}O_{dw}$ (VSMOW) = -8.0‰ to -7.5‰ (Evans, Chenery, *et al.* 2018). $\delta^{18}O$ values from 'local' Cambridgeshire individuals are expected to broadly fall within these values, although with considerable variation. One of the most varied range of $\delta^{18}O$ values seen in Medieval Britain is from Westfield Farm, Ely (Lucy *et al.* 2009). Most of the values are outside of the expected range and are distinct compared to contemporary studies (Jobling and Millard 2020). This remains unexplained and hopefully generating more data for the Cambridgeshire region may help with interpretation.

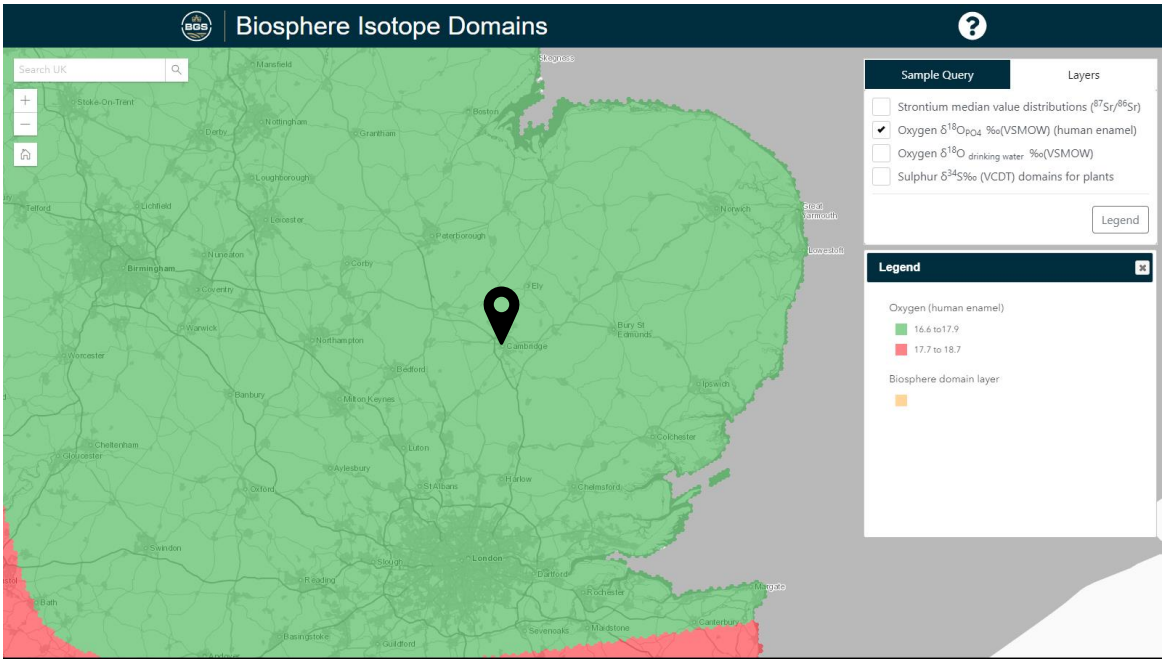


Figure 12: The British Geological Survey Biosphere Isotope Domain GB Online Map showing the layer for $\delta^{18}O$ PO4 ‰ (VSMOW), with Cambridge highlighted (Evans, Chenery, et al., 2018)

[Created using the Biosphere Isotope Domains GB (V1): Interactive Website, British Geological Survey © UKRI 2021. All rights reserved, contains OS Open Data]

Studying a relatively small geographical area largely mitigates the influences of differential altitude, latitude and proximity of the coast on inter-site comparisons and should make identifying outliers more robust. However, short-term climate fluctuations during the Holocene, particularly the warmer 'Medieval Climate Anomaly' (c. AD 950 to 1250) or the subsequent cooler 'Little Ice Age' (c. AD 1400 to 1700 BC) (Bradley *et al.* 2003, Mann *et al.* 2009) could affect the comparability of $\delta^{18}O$ values across the longue durée. Evans *et al.* (2012) suggest that temperature shifts during the Holocene are unlikely to have been large enough to have a large impact upon enamel $\delta^{18}O$ values but concede that these effects could be studied in a restricted locality, which may be possible with the Cambridgeshire data.

In terms of brewing and stewing effects, it is not possible for High/Late Medieval Cambridge to quantify the extent of consumption of water vs ale vs pottage, for example, nor possible to precisely quantify types of cooking methods. Although an informed assumption regarding the general type of diet that people in Cambridge may have had access to in the past can be made using the carbon and nitrogen isotopes, as well as archaeological and historical evidence, this

will not be accurate enough to account for their potential impact on $\delta^{18}O$ values fully. Therefore, the implications of cooking and brewing should be considered, particularly when assessing variability in the range of values but it is ultimately not possible to quantify and therefore mitigate the potential effect on interpreting mobility and environment.

3.5 Strontium Isotope Analysis

3.5.1 Principles of Strontium Isotope Analysis in Archaeology

Strontium has four naturally occurring heavy stable isotopes: ^{84}Sr (0.56%), ^{86}Sr (9.86%), ^{87}Sr (7.0%) and ^{88}Sr (82.58%) (Pollard *et al.* 2007, p. 178). However, unlike the previously described isotopes, ^{87}Sr is radiogenic and can be formed through the radioactive decay of ^{87}Rb (half-life 4.75×10^{10}yr).

Strontium is reported as an absolute ratio of ^{87}Sr relative to ^{86}Sr (Pollard *et al.* 2007, p. 174). The $^{87}Sr/^{86}Sr$ ratio in rocks and minerals is dependent on both time elapsed since formation (due to the radioactive decay) and the isotopic composition of the geological material when formed (Bataille *et al.* 2020). There is a large enough variation in $^{87}Sr/^{86}Sr$ in bedrock to make distinctions based on rock type and age, with old (>100mya) rock with high original Rb/Sr having the highest $^{87}Sr/^{86}Sr$ values (>0.710) and younger rocks with low original Rb/Sr having much lower $^{87}Sr/^{86}Sr$ values (<0.703) (Bentley 2006).

Strontium in rocks and minerals is incorporated into the environment through weathering and is cycled through soil and water before being incorporated into biological tissues (Figure 13). Weathered strontium enters water sources mostly as sediment. Rivers may incorporate strontium from multiple sources and therefore the $^{87}Sr/^{86}Sr$ values of the water will represent a mix of the $^{87}Sr/^{86}Sr$ values of the sources (Wadleigh *et al.* 1985). Different geological sources of strontium weather at different rates and so may disproportionately contribute to rivers that flow over multiple geologies. Seawater represents a mix of all strontium sources and has a homogenous $^{87}Sr/^{86}Sr$ value of c.0.709 (McArthur *et al.* 2001). $^{87}Sr/^{86}Sr$ in soil is predominantly related to weathering of the underlying bedrock, but atmospheric sources such as wind transported dust (Biscaye *et al.* 1974, Dymond *et al.* 1974, Chadwick *et al.* 1999), as well as sea spray and rainfall, can also contribute (Chadwick *et al.* 1999, Whipkey *et al.* 2000, Montgomery *et al.* 2003). $^{87}Sr/^{86}Sr$ values in plants have been shown to reflect the locally bioavailable strontium, averaging out some of the variability in their source $^{87}Sr/^{86}Sr$ (soil, water, atmosphere etc.) (Miller *et al.* 1993, Sillen *et al.* 1998, Bentley 2006). Strontium is incorporated into animal tissues through diet and drinking water (Lewis *et al.* 2017). The averaging of $^{87}Sr/^{86}Sr$ values continues throughout the food chain, as consumers utilise a range of food sources with varying $^{87}Sr/^{86}Sr$

values (Blum *et al.* 2000, Bentley 2006). Importantly for archaeological studies, strontium does not appear to undergo measurable biological fractionation as it is incorporated into subsequent environmental systems (Blum *et al.* 2000, Bentley 2006, p. 141), and any mass fractionation is accounted for by normalisation of $^{87}Sr/^{86}Sr$ values to the ratio of $^{88}Sr/^{86}Sr$ (8.3752) (Steiger and Jäger 1977). This means the values measured in the tissues of consumers should directly reflect those of the food and water they have consumed (Graustein 1989, Blum *et al.* 2000).

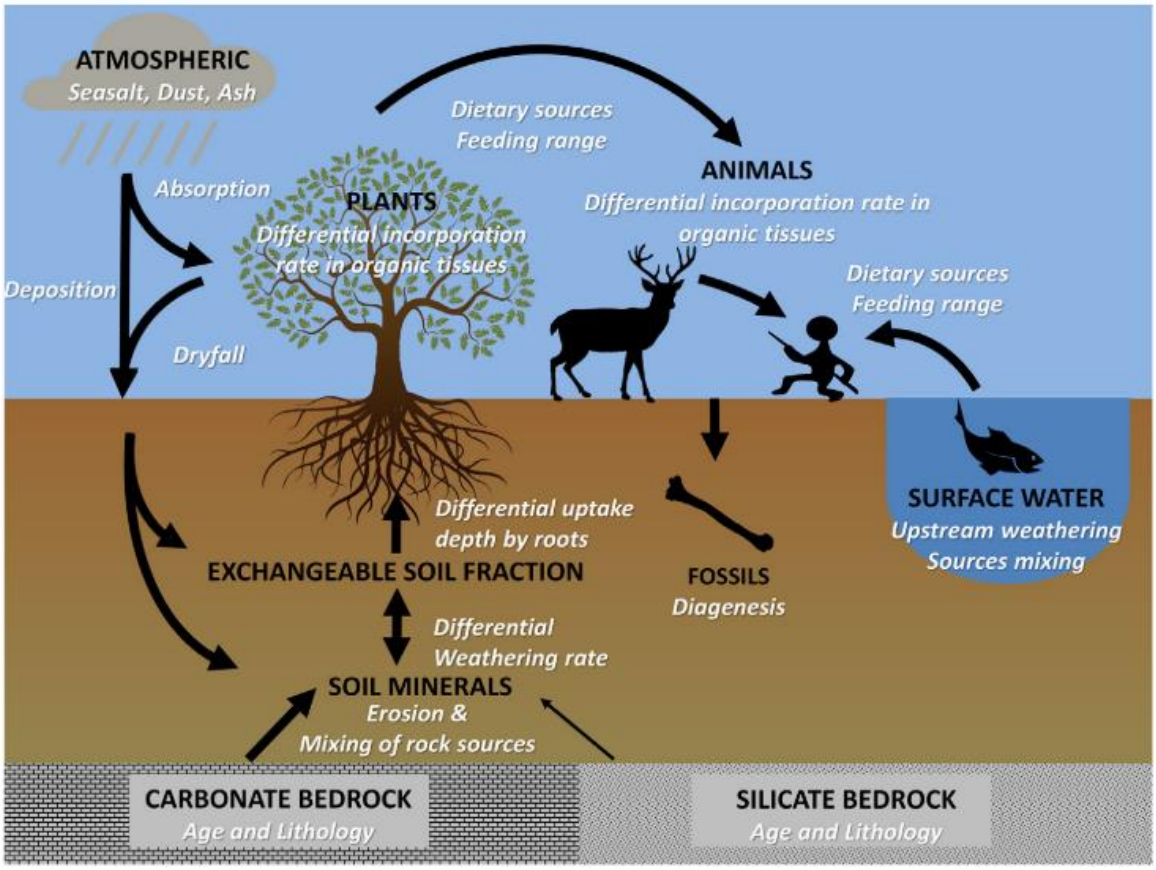


Figure 13: 'Strontium isotope cycling from rocks to ecosystems' (Bataille et al., 2020, p. 3)

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Quantifying and mapping bioavailable strontium using empirical and mechanistic methods has been carried out to varying degrees across the world. This ranges from those which aim to characterise a small region surrounding an archaeological settlement to those which aim to characterise whole countries, or even multi-country regions, including studies in Australia (Adams *et al.* 2019), Cambodia (Shewan *et al.* 2020), the Tarim Basin (Wang *et al.* 2018), South

Korea (Song *et al.* 2014), Japan (Kusaka *et al.* 2011), India (Chase *et al.* 2018), Israel (Hartman and Richards 2014), South Africa (Sillen *et al.* 1998, Copeland *et al.* 2016), Tanzania (Tucker *et al.* 2020), the Americas (Hodell *et al.* 2004, Bataille and Bowen 2012, Bataille *et al.* 2014, Brennan *et al.* 2014, Knudson *et al.* 2014, Hedman *et al.* 2018) and the Caribbean (Laffoon *et al.* 2012, Pestle *et al.* 2013). Europe has also been subjected to large and small scale studies, from testing proof of concepts on the Isle of Skye, Scotland, (Evans *et al.* 2009), to large scale, systematic characterisations of countries, including the UK (Evans *et al.* 2012, Snoeck *et al.* 2020), France (Willmes *et al.* 2018), Denmark (Frei and Frei 2011, 2013), Italy (Emery *et al.* 2018, Cavazzuti *et al.* 2019), Greece (Nafplioti 2011) and the Netherlands (Kootker *et al.* 2016). Recently, Bataille *et al.*. (2020) has synthesised previous approaches to mapping bioavailable strontium and has proposed a complex, global map of predicted $^{87}Sr/^{86}Sr$ values using random forest regression models (Figure 14). Although broad scale, this is a significant enhancement to the study of $^{87}Sr/^{86}Sr$ that is less constrained by geographically limited data.

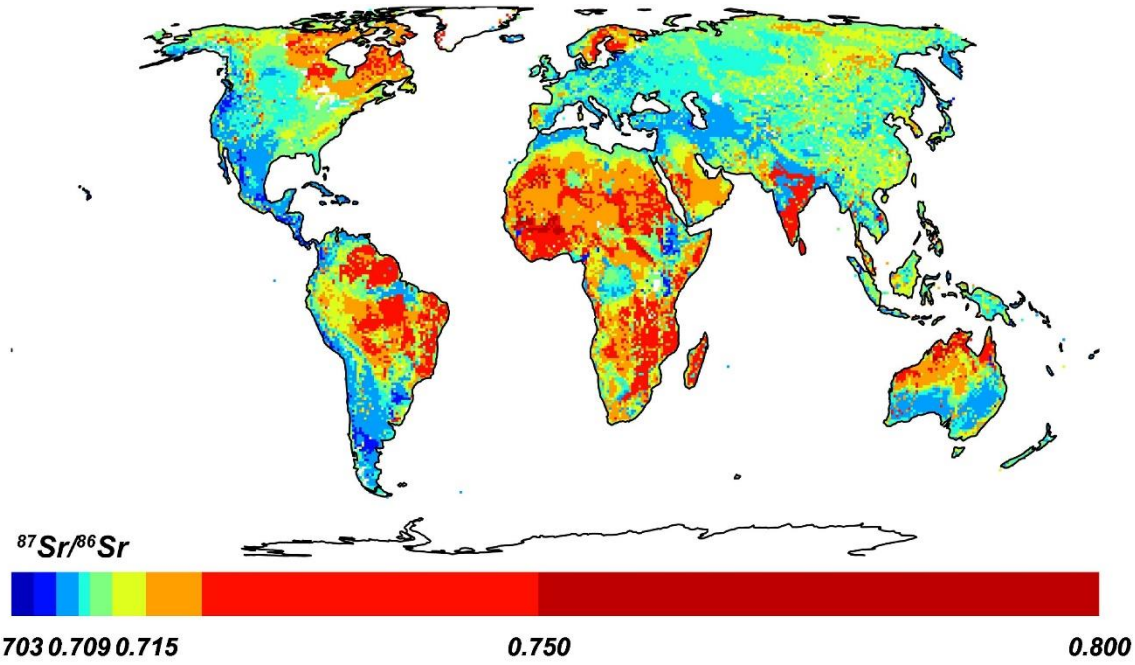


Figure 14: 'Map of predicted bioavailable $^{87}Sr/^{86}Sr$ from random forest regression' (Bataille et al., 2020, p. 11)

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The British Geological Survey (BGS) Biosphere Isotope Domain GB Map (Figure 15), uses over 900 Sr samples (predominantly modern water and plant), combined with a subdivision of

the country into 56 domains based on geology, age and geography, to characterise $^{87}Sr/^{86}Sr$ values for the UK (Evans, Chenery, *et al.* 2018, Evans, Mee, *et al.* 2018). The map is divided into hexagonal units of 1km and is colour-coded based on the median $^{87}Sr/^{86}Sr$ value of that area, which is assigned based on the geological profile and subsequent calculated $^{87}Sr/^{86}Sr$ values which form the majority for that 1km hexagon. The values for Britain range from 0.7070 to 0.7230, with much of the country having a median value distribution of 0.7090-0.7100.

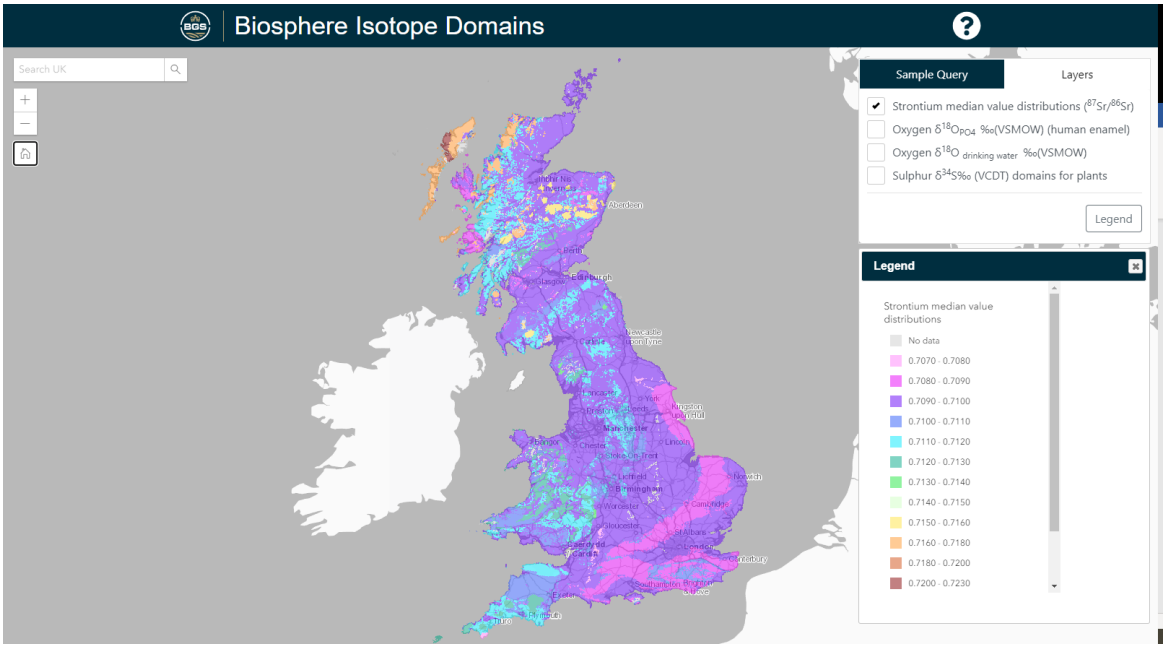


Figure 15: The British Geological Survey Biosphere Isotope Domain GB Online Map showing the layer for strontium median value distributions ($^{87}Sr/^{86}Sr$) (Evans, Chenery, et al., 2018)

[Created using the Biosphere Isotope Domains GB (V1): Interactive Website, British Geological Survey © UKRI 2021. All rights reserved, contains OS Open Data]

As strontium has been proven to be linked to geology and consequently, diet (Sillen and Kavanagh 1982), the idea that strontium isotopes could be used to study human mobility was first suggested by Ericson (1985). Following this, early studies of $^{87}Sr/^{86}Sr$ in archaeological human tissue proved the utility of the strontium isotopes to address questions of migration and mobility (Sealy 1989, Sealy *et al.* 1991, Price *et al.* 1994). Although many archaeological studies subsequently adopted strontium isotope analysis, it was only in 2017 that a controlled animal feeding study showed that there was 'excellent' agreement between $^{87}Sr/^{86}Sr$ in enamel and diet, confirming the principles applied in archaeology (Lewis *et al.* 2017).

Archaeological approaches to the use of strontium isotope analysis to interpret mobility from human tissues are similar to, and often used in conjunction with, those employed in oxygen isotope analysis. $^{87}Sr/^{86}Sr$ values in enamel are compared to expected 'local' bioavailable strontium for the area of burial to identify potential 'non-locals' and can be further interpreted using a provenancing approach. Again, this approach is quite simplistic and sampling bulk enamel only allows for a comparison of location during a relatively short period of childhood and location of death, without providing information about mobility in between. Pollard (2011) cautions that $^{87}Sr/^{86}Sr$ values should not be over-interpreted and if a provenancing approach is to be used, it is more effective as a tool to rule out geographical areas which are unlikely to have produced the values studied, rather than pinpoint specific 'homelands'.

While problems related to fractionation and conversion are avoided with the interpretation of strontium isotope analysis, there are other factors to consider. In particular, human behaviour leading to the utilisation of mixed dietary $^{87}Sr/^{86}Sr$ sources brings complexity to interpreting $^{87}Sr/^{86}Sr$ values (Montgomery *et al.* 2007, Montgomery 2010). For example, humans may choose to eat crops grown on different soils, eat animals grazed on a variety of pastures and/or fodder and choose to drink from a variety of ground and/or river water sources. Their resultant $^{87}Sr/^{86}Sr$ will be a weighted average of these values and could sit anywhere within these end members (Montgomery 2010). The use of mixing models has been proposed to overcome this (Montgomery *et al.* 2007, Montgomery 2010), although this is limited if there are numerous unknown sources. The potential for trade and import of goods from different localities adds further complications and Montgomery reminds us that if a wide distribution of food sources are used 'isotopes cannot reveal whether the food was brought to the person, or the person went to the food' (2010, p. 331). Despite this, it is assumed that in archaeological contexts, the majority of the food sources were locally sourced, leading to a limited number of local $^{87}Sr/^{86}Sr$ end members, thus still allowing for potential identification of 'non-locals'.

As with other isotopes, the addition of fertilisers to soil could change the bioavailable $^{87}Sr/^{86}Sr$, in particular, it has been suggested that fertilisation with seaweed, which has a high strontium content, could have a significant effect on soil $^{87}Sr/^{86}Sr$, causing the soil values to resemble seawater values (Montgomery *et al.* 2003, Evans *et al.* 2010, 2012, Blanz *et al.* 2019). This would be passed up the food chain and could result in human values that trend towards seawater

values, which could make them appear 'non-local'. Agricultural liming may also have an effect on the estimation of bioavailable strontium for archaeological studies, although this has been debated (Thomsen and Andreasen 2019, Frei *et al.* 2020)

In summary, $^{87}Sr/^{86}Sr$ values in human bioapatite should reflect the $^{87}Sr/^{86}Sr$ values of food and water ingested during the formation of the tissue, with no significant fractionation. The $^{87}Sr/^{86}Sr$ values in archaeological tooth enamel should principally be an indicator of the $^{87}Sr/^{86}Sr$ of the locally bioavailable strontium and can be used as a tool for identifying 'non-locals' and for provenancing. However, it should be noted that these $^{87}Sr/^{86}Sr$ values are inevitably the result of the mixing of strontium sources and therefore the interpretation of the results is not necessarily straightforward.

3.5.2 Applying Principles of Strontium Isotope Analysis to Medieval Cambridge

As for oxygen isotope analysis, the small geographical area chosen for this study should mitigate issues of comparison due to variable weathering, dust and sea spray effects. Based on archaeological, historical, and previous isotope evidence from Chapter 2, it is assumed that the majority of the High/Late Medieval individuals will be relatively local to Cambridge. Analysis should enhance understanding of the 'local' bioavailable $^{87}Sr/^{86}Sr$, as well as potentially identify individuals who did not spend their childhood in the same locality as where they were buried.

To put the $^{87}Sr/^{86}Sr$ values from Cambridge into context, it is important to understand the geology and potential range of expected $^{87}Sr/^{86}Sr$ values. The geology of the Cambridgeshire region is predominantly sedimentary, with the base geology formed of Lower Palaeozoic rock (Silurian to Cambrian), with Ordovician-Proterozoic granitic intrusions (Lee *et al.* 2015). The older sedimentary bedrocks of the area are Carboniferous and Devonian (mostly Carboniferous Limestone). The older sedimentary bedrock is overlain by younger sedimentary rocks (Figure 16), forming approximately NE-SW bands across East Anglia. Cambridge itself sits on a transitional zone between several bands of younger sedimentary rocks – directly to the North is Early Cretaceous mudstone (mostly Gault and Hunstanton Formation) and to the South is Late Cretaceous clayey chalk (Grey Chalk Subgroup).

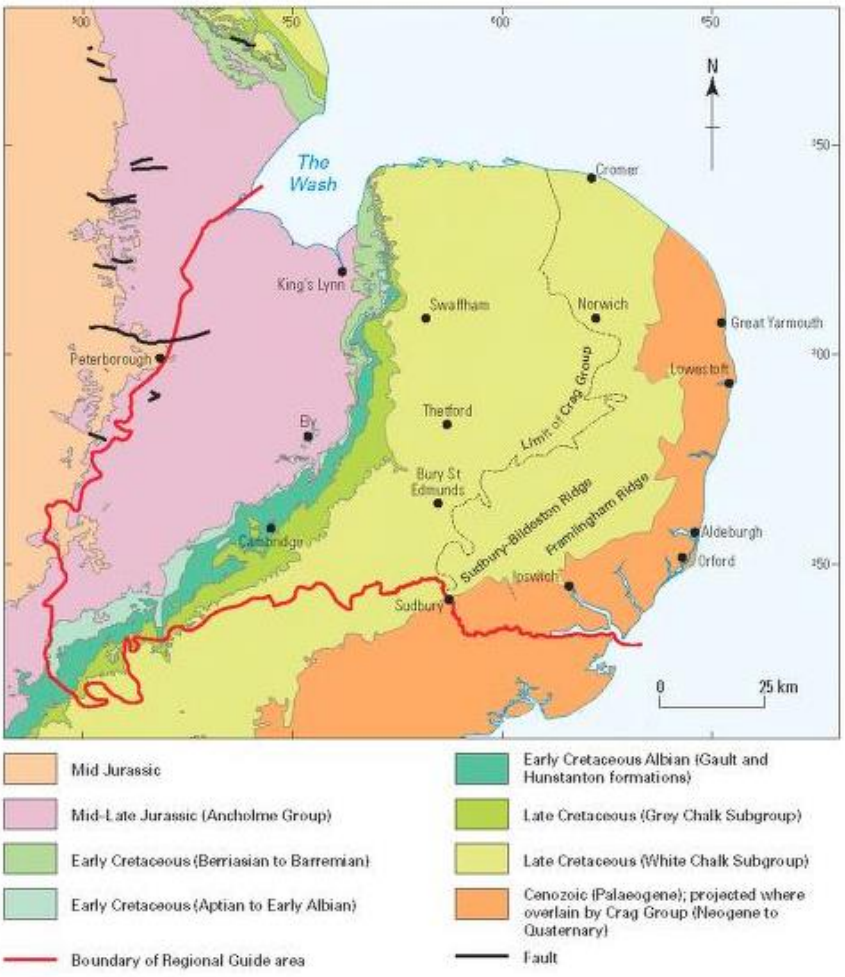


Figure 16: Simplified bedrock geology of East Anglia and adjoining onshore areas showing the distribution of the main rock types and major faults' (Lee, Woods and Moorlock, 2015, p. 3)

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Due to the geology, East Anglia is relatively homogeneous when it comes to strontium isotope characterisation and Cambridge itself is partly situated on two of the most common and undiagnostic areas of $^{87}Sr/^{86}Sr$ values, indistinct from large swathes of the rest of England. According to the BGS Biosphere Isotope Map, central Cambridge has a $^{87}Sr/^{86}Sr$ median value distribution of 0.7080-0.7090 (based on the median $^{87}Sr/^{86}Sr$ values for the local geology and previous environmental samples per 1km hexagon) (Evans, Chenery, *et al.* 2018, Evans, Mee, *et al.* 2018) (see Figure 17). There are areas with $^{87}Sr/^{86}Sr$ median value distributions of 0.7090-0.7100 nearby, including the area to the North-East of the centre of Cambridge and a small area to the South of central Cambridge. However, due to the assignment of values to 1km units, it is

unlikely that speculating on the values of specific sites within Cambridge to this level of precision is valid. Much of the Cambridge environs also has a $^{87}Sr/^{86}Sr$ median value distribution of 0.7080-0.7090. However, there are pockets of localised geology in East Anglia with a $^{87}Sr/^{86}Sr$ median value distribution of 0.7100-0.7110, including around Gamlingay and Potton, c.30km to the South-West of Cambridge, as well as areas around Cottenham (c.11km), Ely (c.27km), Downham Market (c.56km) and Kings Lynn (c.72km), all to the North. All these areas had Medieval settlements, and many were important trade centres. Based on the BGS Biosphere Isotope Map, the location of Cambridge on a geological boundary, as well as ambiguities relating to calculating the $^{87}Sr/^{86}Sr$ value distribution in such a homogenous area and the added complication of estimating water management and utilisation in the past, a reasonable estimate of the 'localised' signature for Cambridge would have to be 0.7080-0.7100. Unfortunately, there are no recent published studies that have produced $^{87}Sr/^{86}Sr$ values for any archaeological material in East Anglia to confirm expected values. The spatially nearest area which has produced some archaeological $^{87}Sr/^{86}Sr$ values is Greater London (c.100km from Cambridge), which is dominated by Palaeogene clay (London Clay Formation). On the BGS map, the $^{87}Sr/^{86}Sr$ median value distribution for most of inner London is estimated at 0.7090-0.7100 (Evans, Chenery, *et al.* 2018) and the values of the Medieval skeletons analysed from East Smithfield and St Mary Spital largely appear to fit with this (mean=0.7093, n=38) (Kendall *et al.* 2013).

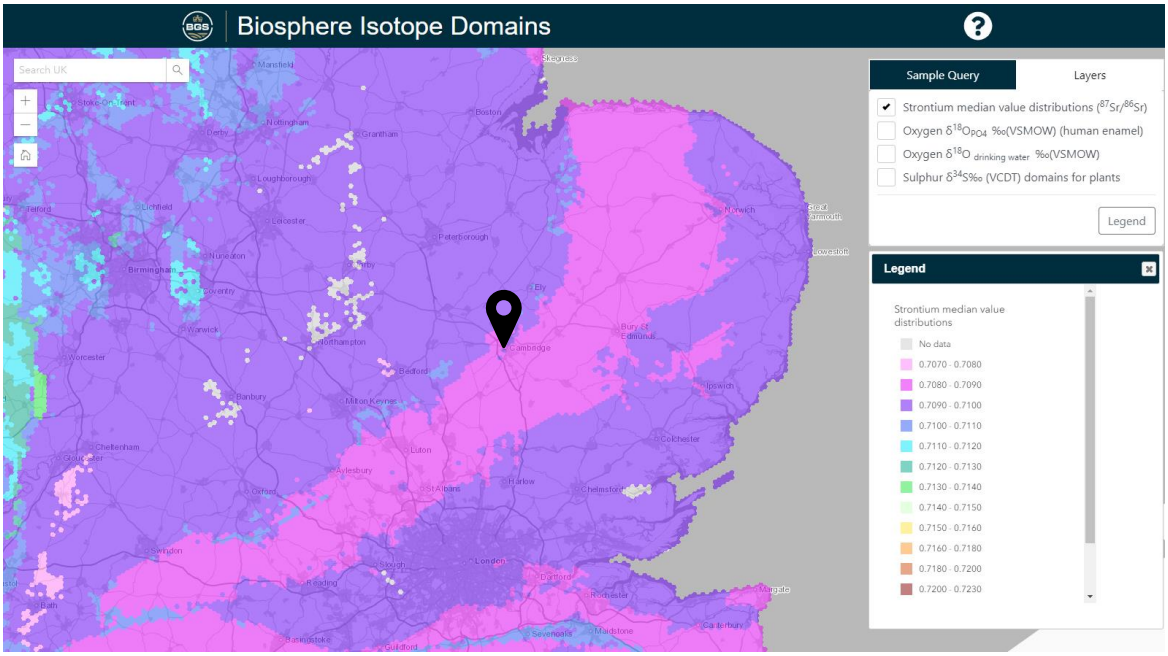


Figure 17: British Geological Survey Biosphere Isotope Domain GB Online Map showing the layer for strontium median value distributions ($^{87}Sr/^{86}Sr$), with Cambridge highlighted (Evans, Chenery, et al., 2018)

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However, a range of 0.7080-0.7100 is not distinct to Cambridge. Bioavailable $^{87}Sr/^{86}Sr$ values between 0.7080-0.7100 are common and can be found all over the world. Using $^{87}Sr/^{86}Sr$ values from ~1200 systematically collected soil samples from across Europe, Hoogewerff *et al.* have developed a Bayesian likelihood ratio method to create likelihood ratio (LR) maps for European $^{87}Sr/^{86}Sr$ values, illustrating the ratio of the probability of 'cells' in the map matching a sample value and the probability of observing that 'cell' value (Hoogewerff *et al.* 2019, p. 1042). To illustrate this, Hoogewerff *et al.* use a 'very prevalent soil value' of 0.7090 ± 0.0010, resulting in a map with a diluted LR spread across almost all of Europe (Figure 18). Applying the theory of Occam's razor, an individual buried in Cambridge with a $^{87}Sr/^{86}Sr$ value of 0.7080-0.7090 is likely to have spent their childhood there. However, according to their $^{87}Sr/^{86}Sr$ values alone, they are as likely to have spent their childhood in many parts of the world. Conversely, a relatively common 'local' value should mean that any outliers are distinct, and the interpretation of their origins may be enhanced as large parts of the world would be excluded as potential 'homelands'. In addition, the combination of $\delta^{18}O$ values with the $^{87}Sr/^{86}Sr$ values may differentiate between potentially generic signatures.

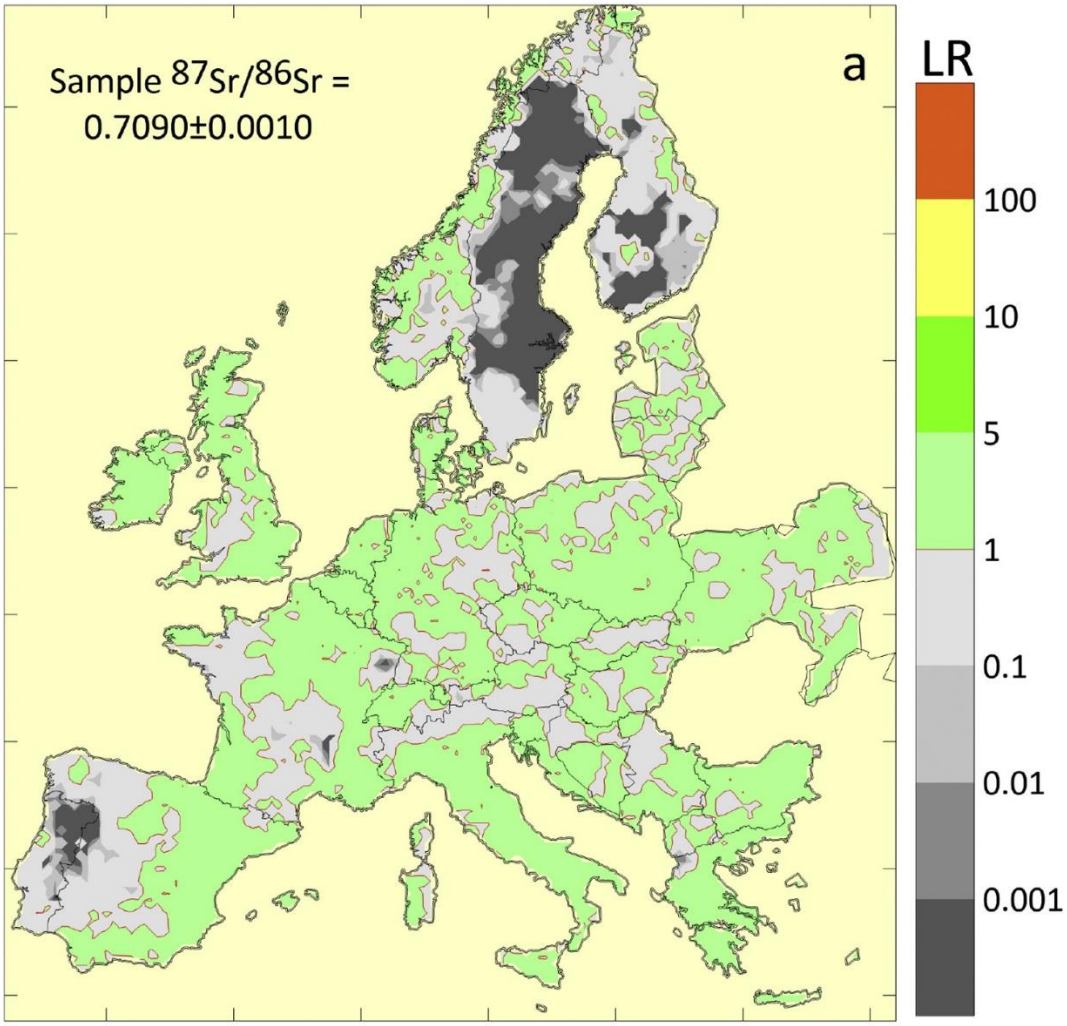


Figure 18: 'LR on an order of magnitude scale based on measured and model 87Sr/86Sr values and errors: Likelihood Ratio map for the common $^{87}Sr/^{86}Sr$ value of 0.7090' (adapted from Hoogewerff et al., 2019, p. 1042)

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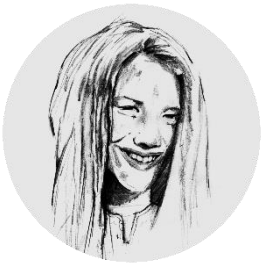
3.6 Quantifying Variability and Difference in Isotope Analysis

When interpreting isotope values in archaeology it is also important to consider the scale of difference and identify at what point changes are biologically meaningful for understanding past diet and mobility. Firstly, analytical error should be calculated. Recent IRMS analyses at the Godwin Laboratory, University of Cambridge indicate analytical error of <0.2‰ for collagen $\delta^{13}C$ and $\delta^{15}N$ and <± 0.1‰ for enamel carbonate $\delta^{18}O$ analyses (Lightfoot, Čaval, *et al.* 2020, Lightfoot, Pomeroy, *et al.* 2020, Leggett *et al.* 2021, this study) while replication of standards run during TIMS analysis at the Department of Earth Sciences, Cambridge indicate an error of <0.00001 for $^{87}Sr/^{86}Sr$ (this study). Any variation in isotope values within this error cannot be considered to be meaningful for interpretations. Secondly, the expected degree of natural variation in values, even for an essentially homogenous population (living and eating similarly), should be considered. Feeding studies by DeNiro and Schoeninger (1983) suggest that baseline biological variation in bone collagen $\delta^{13}C$ and $\delta^{15}N$ values obtained from rabbit and mink eating monotonous diets could be up to 1.4‰ and speculate variation in human populations eating similar diets could be ~±1.0‰. As discussed above, it has been shown that intra-population variation in phosphate $\delta^{18}O$ values from archaeological samples is typically at least 2.0‰, but more likely at least 3.0‰ (Lightfoot and O'Connell 2016). Feeding studies of rats have shown intra-population variation in enamel $^{87}Sr/^{86}Sr$ of <0.001 (Weber *et al.* 2020), while a study of pigs fed an identical diet has shown an inter-population variation of <0.0001(Lewis *et al.* 2017). Variations in human enamel $^{87}Sr/^{86}Sr$ in archaeology are typically regarded to be meaningful to the fourth decimal place (Price *et al.* 2012). Finally, the chronological, geographical and archaeological context should be considered in order to assess the scale of change, along with the relative sample size and values from other comparable studies. These quantifications of intra-population variation should be considered when analysing the results from Cambridge. Values above the general estimations of intra-population variability may be considered to be strong indicators of difference. Isotope values that are greater than analytical error but within estimations of general intra-population variation may not be confidently attributed as being meaningful in terms of quantifying absolute differences although values should also always be

considered in terms of contextualised variance, which may still identify useful intra-site patterns and outliers (Lightfoot and O'Connell 2016).

3.7 Summary of the Principles of Isotopes

In summary, analysis of the isotopes of the four elements described is a well-established and powerful technique in archaeology for understanding diet and population mobility in the past. These isotopes should be useful for understanding what life was like in High/Late Medieval Cambridge, particularly regarding animal protein consumption, marine fish consumption and identification of potential 'non-locals'. However, limitations of the techniques should always be acknowledged, and caution should be taken not to over-interpret the results.



4. Research Design

This chapter discusses and justifies the methods and materials chosen to answer the research questions posed in this thesis and provides contextual information about the sites selected. The next chapter (5) will then discuss exactly what new material was actually sampled and how the methods proposed in this chapter were implemented.

4.1 Ethical Stance

Following guidelines by the Advisory Panel on the Archaeology of Burials in England (APABE) and the British Association for Biological Anthropology and Osteoarchaeology (BABAO), I firmly take the stance that studying human remains is a privilege, not a right, and that human remains require greater ethical considerations than most other archaeological material (Mays *et al.* 2013, Redfern 2019, Redfern and Jones 2019).

4.2 Justification of Destructive Sampling

The ethics of destructive sampling is a continuing debate within the archaeological and museum communities, particularly in light of increasing numbers of destructive scientific techniques (Mays *et al.* 2013, Austin *et al.* 2019, Fox and Hawks 2019). 'Science and the Dead' destructive sampling guidelines (Mays *et al.* 2013) emphasise that:

- Research questions should be significant and worthwhile
- Methods should be considered and suitable
- Materials should be suitable and will provide the results required
- Samples taken should be of a reasonable size and are as minimally destructive as possible
- Good records should be produced

- Future research should be taken into account

This thesis aims to adhere to as many of the relevant points as possible, as well as adhering to any specific stipulations made by the institutions curating the collections, particularly the Duckworth Laboratory, University of Cambridge, who have a strict policy regarding destructive sampling (The Duckworth Laboratory Terms and Conditions 2018).

While questions about diet and migration could partially be investigated using evidence such as historical documents or zooarchaeological assemblages, the 'After the Plague' project and I decided that only destructive scientific analysis could provide direct and comparable evidence for an individual's experience and answer the research questions posed.

In most cases, it was judged by the collection managers, the 'After the Plague' project and myself that the potential knowledge to be gained justified a destructive sampling strategy. This was due to several reasons, including:

- The collections are largely Medieval and most have a reasonable number of skeletons present (>25), therefore are not considered to be as 'rare' as a single Palaeolithic burial for example, so destructive sampling would not dramatically reduce material for future study
- Many of the collections have not previously been sampled for scientific analysis
- Several of the collections have never been systematically studied or published despite being excavated decades ago, therefore any information generated adds to the knowledge of the collection

The sampling strategy was designed to require only the minimum amount of material for each type of isotope analysis and excess material was to be returned to the collections. A recording strategy was devised requiring all elements to be sampled to be recorded, photographed and in the case of material from the Duckworth Laboratory, μCT scans and high-resolution moulds to be taken of the teeth (The Duckworth Laboratory Terms and Conditions 2018). Future research was considered, meaning the destruction of features such as major anatomical landmarks or pathological lesions was to be avoided and where only a few bones or teeth are available, the need for isotope information versus destruction of a finite source of evidence was to be considered.

4.3 Choosing an Isotopic Methodology

Chapter 2 has shown that historical and archaeological evidence for diet and mobility is available but the evidence for Cambridge is patchy. Apart from exceptional circumstances, these sources do not provide dietary or mobility information at the site or individual scale. As discussed above and in Chapter 3, isotope analysis can provide information about diet and mobility which may not be accessible through other forms of evidence, making it a powerful tool for this thesis. However, the methods can be quite crude and are best used in conjunction and in context with the other evidence. Therefore, to answer questions about diet and mobility in Cambridge, I decided a multi-isotope approach utilising carbon and nitrogen isotope ratios in bone and dentine collagen, oxygen and carbon isotope ratios in enamel carbonate and strontium isotope values in enamel was deemed most suitable, allowing for high-volume, multi-scalar information.

The methods of isotope analysis chosen for this thesis are well established in archaeological research, with well-documented results (see Lee-Thorp 2008). The McDonald Institute, University of Cambridge is well provisioned to carry out in-house carbon and nitrogen isotope analysis in collagen and carbonate oxygen and carbon isotope analysis, with a proven record of robust results. Strontium isotope analysis is less established in the McDonald Institute, although initial work by Argyro Nafplioti had established that in-house analysis was possible in collaboration with the Isotope Geochemistry Laboratory in Earth Sciences, University of Cambridge.

4.3.1 Pilot Study

Further justification of the suitability of isotope analysis for this subject has been shown through previous research in Cambridge and a pilot study. 106 individuals from the Hospital of St John the Evangelist, Cambridge were previously sampled for carbon and nitrogen isotope analysis by Price (2013) to investigate 14th century social change in Cambridge but found no significant intra-population differences. Building upon this, I conducted a pilot at the start of this PhD, sampling rib bone collagen from a further 52 individuals from the Hospital of St John, as well as bone collagen from 19 animals from contemporary Medieval contexts from the adjacent site of St John's Triangle, to provide a comparative faunal isotopic baseline. These

analyses, as well as those by Price, were successful, with only three human samples failing to produce isotope results (these were later re-analysed successfully). Principally, these studies proved the Medieval skeletal material in Cambridge was of good enough quality to produce isotope results, demonstrating suitability for further multi-tissue analysis. The results of the analyses also showed the potential of the data to characterise the diet in Medieval Cambridge, as well as for evaluating changes through time and the effects of calculating appropriate human-faunal offsets. Ten femur midshafts from Holy Trinity Church were also analysed for collagen $\delta^{13}C$ and $\delta^{15}N$ as part of pilot analysis in order to assess whether multiple bone samples (rib & femur) should be analysed for this thesis. From this, I decided that sampling femurs (in addition to ribs and dentine) was unnecessarily destructive and sampling multiple bones from each individual for collagen $\delta^{13}C$ and $\delta^{15}N$ would be beyond the scope of this thesis. The femur data is not included in this thesis but can be found in the full dataset available on Apollo (https://doi.org/10.17863/CAM.71053). Ultimately, the study by Price and the pilot study conducted for this PhD confirmed that the materials and methodologies chosen for this PhD are appropriate and have great potential to address the research aims and questions.

4.4 Establishing a Chronological Framework

To standardise the data and allow for comparisons between the material sampled, as well as with comparative studies, I decided that all human and faunal samples in this thesis should be assigned to standardised chronological periods. Due to differing needs and additional sites used, it should be noted that the divisions used in this thesis do differ from the chronological divisions chosen by the 'After the Plague' project. For this thesis, I decided that the list of main archaeological and cultural periods of Britain developed by Historic England (2013) should be used as a baseline, with more specific divisions of c.200-250yr for the Medieval period. The resulting chronological framework can be seen in Table 4. As Cambridge sat in a region affected by the fluctuating borders of Anglo-Saxon Kingdoms, I decided that the Early Medieval period should be subdivided to investigate changes in more detail. The Early Medieval period was split into Early, Middle and Late Anglo-Saxon based on broad historical events including the conversion to Christianity in the early 7th century and political reform and Viking invasions in the 9th century, with the end of the Early Medieval period taken as the Norman Conquest of AD 1066. The High and Late Medieval periods are here divided by the accession of Edward I

to the throne in AD 1272, marking a period of social and political change, although for much of the thesis these categories will be considered together as many of the key sites span both the High and Late Medieval periods. The phrase 'longue durée' is used in this thesis to describe periods spanning beyond the High/Late Medieval category. While the phrase is used with the purpose of exploring long-term chronological change, it is used broadly, and the more complex theoretical framework associated with the approach of the 'longue durée', as outlined by Fernand Braudel (Braudel and Wallerstein 2009) will not be explicitly applied, as the data from beyond the High/Late Medieval period are not the main focus of the thesis. As also discussed by Braudel (Braudel and Wallerstein 2009), it is acknowledged that choosing the divisions of British time periods and indeed, imposing divisions in archaeology at all, is problematic (e.g. Lucas 2019). This is particularly true of the division of the Early Medieval Period (see Bayliss *et al.* 2013, pp. 27–33), partially due to disagreements regarding major events in the period, e.g. how/when/if major migration occurred (Hills 2003, Thomas *et al.* 2006, Pattison 2008, Härke 2011) and partially due to difficulties in the calibration of radiocarbon dates in the Early and Late Early Medieval periods (Bayliss *et al.* 2013, pp. 44–49). It is recognised that the term 'Anglo-Saxon' itself is now controversial (ISSEME | News 2019, Hines 2020). For want of a better term, this thesis will use 'Anglo-Saxon', but it is recognised that this is not ideal and will be reviewed in further publications. The general chronology of each site will be discussed in the site summaries in Section 4.5.2 and a subsequent timeline and categorisation of each site subgroup to the chronological framework is presented in Sections 5.1.1.5 and 5.1.2.

British Archaeological/ Cultural Period (Historic England 2013)	Subdivided Archaeological/ Cultural Period as Utilised in This Thesis	Approx. Start Date	Approx. End Date
Neolithic	Neolithic	-4000	-2200
Bronze Age	Bronze Age	-2600	-700
Iron Age	Iron Age	-800	43
Roman	Roman	43	410
Early Medieval	Early Anglo-Saxon	410	660
	Middle Anglo-Saxon	660	900
	Late Anglo-Saxon	900	1066
High/Late Medieval	High Medieval	1066	1272
	Late Medieval	1272	1540
Post-Medieval	Post-Medieval	1540	1901

Table 4: Broad and specific British archaeological/cultural periods used (BC/AD), based on Historic England period list (2013)

4.5 Material Selection

As this PhD research is part of the larger 'After the Plague: Health and History in Medieval Cambridge' project, the sampling strategy was principally designed to address the wider questions of the project as well as the questions posed in this thesis. Justifications of the sampling strategy are outlined below.

4.5.1 Site Selection

As discussed in Chapter 2, Cambridge and its environs are likely to have had a diverse and socially stratified population, divided into a complex variety of social groups and changing through time. The selection of archaeological sites for isotope analysis was principally designed to investigate this, within the parameters of availability. The key selection criteria were: suitability for the research questions, time period, type of site, amount of available skeletal material present, proximity to central Cambridge, the feasibility for destructive sampling and ease of access to the collection. Collections of human skeletal remains for new analysis were principally selected by John Robb, Sarah Inskip and Craig Cessford of the 'After the Plague' project and not by myself. The priority for human skeletal material was to select several 'town' and 'rural' High/Late Medieval sites from Cambridge and the surrounding area so that a wide demographic was represented. It was also deemed important to compare these High/Late Medieval sites to the longue durée, so sites in the region from a wide time span were also selected. Unfortunately, some time periods are better represented than others in the Cambridge

region, in particular, for isotope analysis, it was not possible to sample skeletons dating to the Bronze Age (c. 2600-700 BC). The Post-Medieval period (mid-16th century onwards) is also not well represented. As most human burial sites are poor contexts for securely dated faunal remains, I chose additional sites, in conjunction with Craig Cessford, to provide faunal and fish bone. Most collections utilised in this thesis were either held by the Duckworth Laboratory (University of Cambridge), the Department of Archaeology (University of Cambridge), the Cambridge Archaeological Unit or the Cambridge County Council.

I decided that data from sites previously studied for isotope analysis in the Cambridge region should be added to the primary dataset, primarily to increase the longue durée sample (see Section 4.5.2 for further information).

4.5.2 Site Summaries

A large number of suitable archaeological sites across Cambridge and the surrounding area were selected for human and faunal skeletal material for isotope analysis based on the criteria outlined above.

A summary of the key information about each site and why it was selected has been provided here for context, however, more detailed summaries of the sites will be available in Cessford (in Robb n.d.). Detailed information relating to actual numbers of samples taken are discussed in Chapter 5 (see Section 5.1.2, Table 8).

4.5.2.1 Site Locations

Figure 19 shows all the sites utilised in this thesis. For maps showing the development of the Cambridge town sites through the Medieval period, see Chapter 2, for details about the number of samples taken for isotope analyses, see Table 8, Chapter 5.

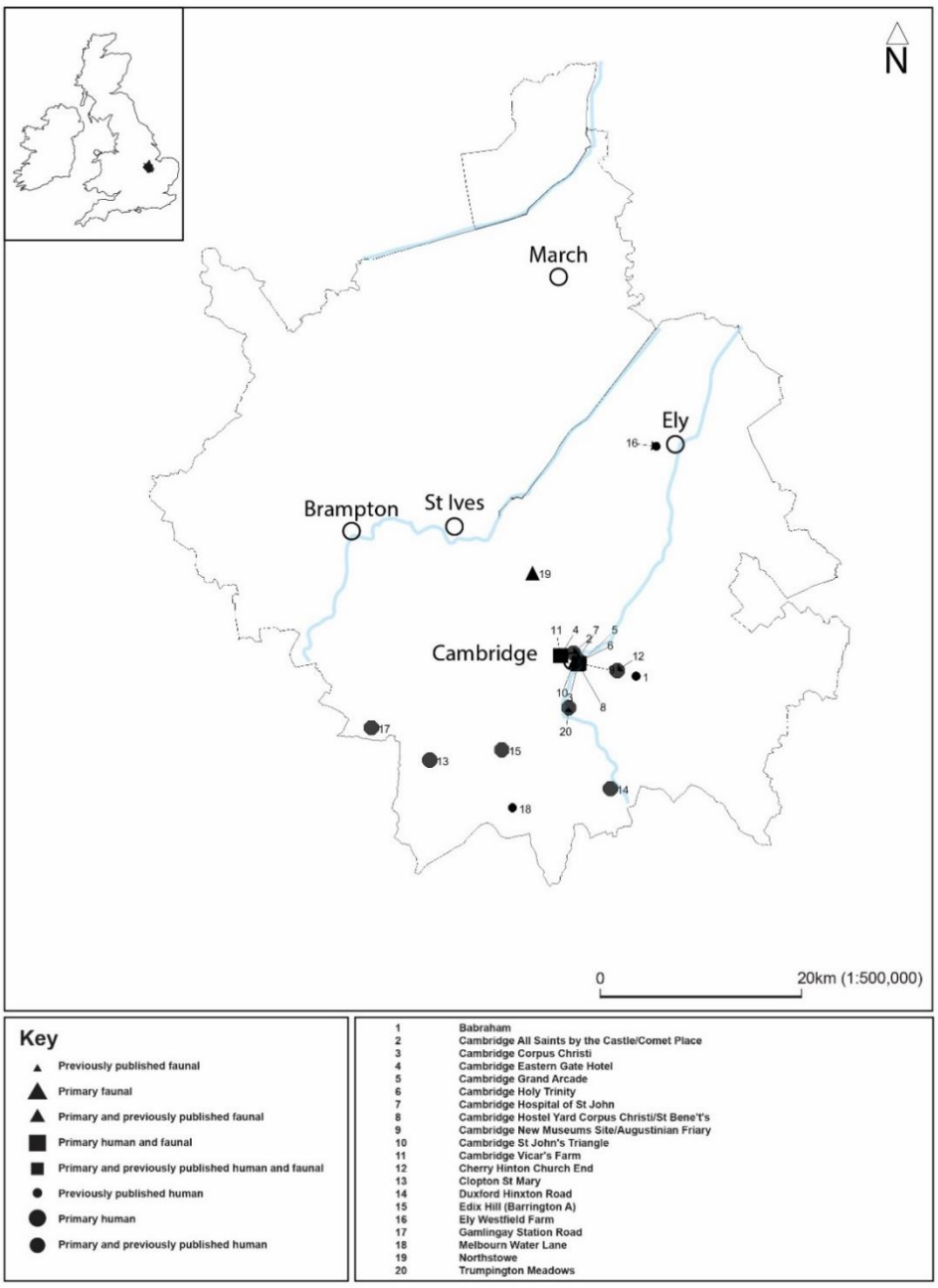


Figure 19: Map showing the location of all Cambridgeshire sites which have provided isotope data used in this thesis (map produced by Kevin Moon)

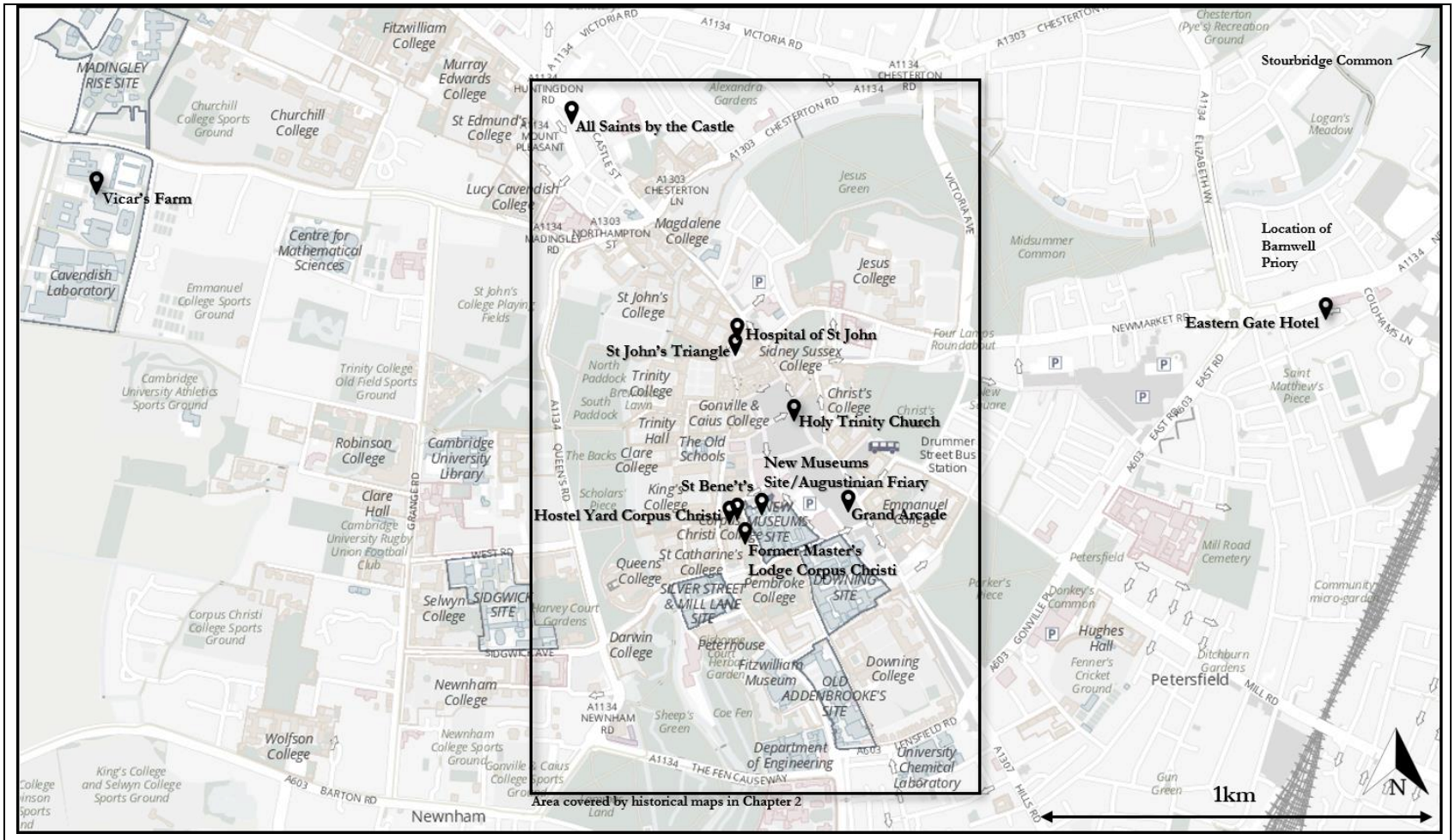


Figure 20: Map of modern Cambridge showing the location of sites discussed in this thesis and location of area shown on historical maps in Chapter 2.

[Created using the University of Cambridge University Map, provided and managed by University Information Systems. Map base data copyright © OpenStreetMap contributors, (including University of Cambridge), licensed ODbL v1.0. Map presentation copyright © 2012-2020 University of Cambridge]

4.5.2.2 High/Late Medieval Cambridge: Town Sites

All Saints by the Castle/Comet Place, Cambridge (TL 4438 5929; Site Code: CP73)

Selected for: human material

All Saints by the Castle was selected to represent a 'normal' Medieval town parish population. All Saints was a parish church in Cambridge, located on the North side of the river Cam. It is likely the church and cemetery were founded c. AD 940-1100 and went out of use by AD 1365, when the parish was amalgamated with St. Giles (Cessford in Robb n.d.). The cemetery at All Saints by the Castle was first identified during evaluation trenching in 1972 and was subsequently excavated in 1973, 1988 and 1994, although the associated church has never been located. Approximately 210 skeletons were excavated, with most of the burials likely to date to after AD 1066 (Cessford and Alexander in Robb n.d.). The cemetery population probably consisted of a socially and economically mixed group of parishioners, who were more likely to have been involved in agricultural activities than those in the centre of Cambridge.

St John's Triangle, Cambridge (TL 445 585; Site Code: SJT07)

Selected for: faunal material

Faunal material from St John's Triangle was selected to produce a faunal 'isotopic baseline' for the High/Late Medieval period. The site was selected particularly for its spatial and temporal proximity to the Hospital of St John. St John's Triangle was located just North of the centre of Cambridge. Between the 13th and 15th centuries, it was a prosperous and perhaps 'exclusive' mercantile district which occupied by several properties, including shops. The cemetery of St John's Hospital was also established in the same street block in the 13th century (Cessford 2015) St John's Triangle was excavated by the Cambridge Archaeological Unit (CAU) between 2005 and 2008 (Newman 2008a). Excavations revealed dense urban occupation throughout the medieval period. Due to the complexity of the stratigraphy, the site is well-dated with distinct phases. 8,647 animal bone fragments were recovered from the excavations, with the majority of the stratified material coming from the High/Late Medieval and Post-Medieval periods (Newman 2008b).

The Hospital of St John the Evangelist, Cambridge (TL 4484 5874; Site Code: JDS10)

Selected for: human material

The discovery of human skeletal remains from The Hospital of St John the Evangelist was the original catalyst for the 'After the Plague' project. The site was selected as it spans the High/Late Medieval period and provides a potential cross-section of High/Late Medieval society.

The Hospital was founded in c.1190-1200 just North of the centre of Cambridge and was superseded by St John's College in 1511 (Babington 1874, Miller 1961). When founded, it would have sat between the churches of All Saints in the Jewry, St Clement and the Church of the Holy Sepulchre (the Round Church). Initially, it may only have been a secular establishment, but it was later upgraded to a *locus religiosus* - a place which provided both physical and spiritual care, following the rule of St Augustine (Rubin 1987). Clerical and lay brethren would have provided basic care and treatment, primarily focussed on spiritual healing along with rest and nutrition (Rubin 1987). Rules at St John's Hospital stated that admission was for the sick and the weak excluding 'pregnant women, lepers, wounded people, cripples and the insane' (Rubin 1987, p. 157). The hospital also offered 'corrodies', where people could pay to reside in the hospital, essentially in the manner of a retirement home (Underwood 2008, McIntosh 2012).

Excavations at the Old Divinity School (St John's College) by the CAU between 2009 and 2011 revealed a detached cemetery belonging to St John's Hospital (Cessford 2015). Historical documents and radiocarbon dating indicate it is likely to have been in use between c.AD 1204-14 and 1511 (Cessford and Alexander in Robb n.d.). The excavations revealed at least 400 articulated skeletons, although over half were less than 25% complete (Dodwell 2015). It is likely the detached cemetery population comprises primarily of Hospital inmates, as well as possibly staff and benefactors (Cessford 2012). A substantial 13th-14th century pit was also discovered containing four skeletons. The pit appeared to be repurposed from an industrial function and it is likely the burials were contemporary. The nature of this event is unknown but it is unlikely to be directly related to Hospital activity (Cessford 2012).

New Museums Site/Augustinian Friary, Cambridge (TL 44942 58301; Site Code: NRB16)

Selected for: human and terrestrial faunal material

The Augustinian Friary was selected to represent an explicitly religious institution with potential for a mobile population and evidence of a monastic diet. Faunal material was selected to add to the faunal 'isotopic baseline' for the High/Late Medieval period.

The Friary was established between AD 1279/80-1289 and eventually occupied a comparatively large plot of land, stretching beyond the Kings' Ditch to the South and to the market square in the North (Cranage and Stokes 1921). The Hermit Friars of St Augustine (*Ordo Eremitorum Sancti Augustini* or OESA) were a mendicant order, meaning adherence to principles of poverty and charity, and Friary was one of several Friaries of various orders established in Cambridge in the 13th century (Salzman 1948, pp. 197–199, 287–290). The Augustinian Friary in Cambridge was an important establishment, with international recognition. In 1318, the Friary was declared a *studium generale* by the Pope. It was the third most important such *studium generale* of the Order, after Paris and Oxford, and attracted students from district and international provinces (Roth 1966). The Friary is the only establishment studied in this thesis that was directly affected by the Dissolution in 1538, although it was already almost defunct by this time (Cranage and Stokes 1921).

Excavations in 2016-2019 of the Old Examination Hall, New Museums Site, by the Cambridge Archaeological Unit (CAU) revealed significant evidence of the Friary, as well as pre- and post-Friary phases, spanning from c.AD 1050 to the Post-Medieval (Cessford 2017, 2020). The Friary phases were robustly dated to c.1275-1538 (*ibid.*). Thirty-two predominantly male skeletons were recovered from a cemetery dating to c.1290-1360/1420 and six skeletons were recovered from the chapter house, dating to c.1360/1420-1538 (Cessford in Robb n.d., Cessford 2017, 2020). Individuals buried in the Friary are likely to be a mix of members of the OESA and lay individuals, including benefactors and corrodians (Cessford in Robb n.d.). It appears that members of the OESA could be distinguished by clothed burial with a buckle, whilst those without are likely to be lay individuals (Cessford *et al.* in prep.).

7784 animal bone fragments were also recovered during Phase 1 of excavation, of which 1927 were identified to species, including a wide variety of domestic and wild species (Rajkovača 2017, pp. 70–77). Much of the faunal assemblage was recovered from pre-Friary contexts,

predominantly dating to the 13th-14th century (*ibid.*). A further 3505 animal bone fragments were recovered in Phase 2 and 422 fragments of a subsample were identified to species (Rajkovača 2020, pp. 27–32).

St Bene't's/Hostel Yard Corpus Christi, Cambridge (TL 44838 58274; Site Code: HYC05)

Selected for: human material

The skeletons from St Bene't's were selected as they may represent the only accessible 'plague-pit' assemblage from Cambridge.

A watching brief in the Hostel Yard/St Bene't area by the CAU in 2006 revealed part of a large pit containing at least five skeletons, although only the crania were exposed (Cessford and Fallon 2006). The identification of *Y.pestis* through pathogen DNA analysis (Scheib in Robb n.d.), as well as textual evidence, dates the skeletons to c.1348-1377 (Cessford and Alexander in Robb n.d.). The area is currently part of Corpus Christi College, located in the centre of modern Cambridge, immediately South of Bene't Street. However, the construction of the College itself did not begin until 1352 meaning these skeletons are likely to have pre-dated the College and were buried on land formerly belonging to the adjacent St Bene't's Church. It has been theorised this was a mass burial pit for plague victims that was incorporated into the College as a form of commemoration (Cessford in Robb n.d.).

Eastern Gate Hotel Site, Cambridge (TL 46453 58895; Site Code: EGN12)

Selected for: aquatic faunal material

Fish bone from the Eastern Gate hotel site was selected to provide a faunal 'isotopic baseline' for the High/Late Medieval period. Unfortunately, accessible fish bone material was very scarce, so the site was selected simply because it had available material from the appropriate time period.

The site was located to the east of Cambridge, in the Medieval settlement of Barnwell. Medieval occupation at the site is likely to have started following the relocation of Barnwell Priory to the area in c.1112. Five 'burgage' plots, comprising domestic buildings, accessory buildings, and land for domestic and horticultural activities were established on the site in the early 13th century, and it continued to be an area of domestic and craft activity into the Post-Medieval

period (Newman 2013). Excavations were carried out at the site of the Eastern Gate Hotel by the CAU in 2012 (Newman 2013). Multiple phases of activity were identified, with the height of activity occurring during the Medieval Settlement phase, before the Dissolution of the Priory in 1538. During excavation, 555 individual fish specimens were recorded, although 281 were indeterminate (Hamilton-Dyer unpub.).

4.5.2.3 High/Late Medieval Cambridge: Rural Sites

Church End, Cherry Hinton, Cambridge (TL 4872 5758; Site Code: HAT358/1)

Selected for: human material

Church End, Cherry Hinton was selected to represent a rural population within the Cambridge hinterland.

Cherry Hinton is located c.4.5km southeast of modern central Cambridge. The area has been subject to substantial phases of excavation since the 1990s, building evidence for long-standing rural Medieval settlement at the site (Cessford and Dickens 2005, Cessford and Slater 2014). Excavations at 69-115 Church End, Cherry Hinton were carried out in 1999 by Hertfordshire Archaeological Trust (now Archaeological Solutions) (McDonald and Doel 2000), although it has not yet been fully published. These excavations revealed a small church structure and over 670 associated burials, dating to *c.* AD 940/990–1120/1170 (Cessford and Alexander in Robb n.d., Cessford and Slater 2014). The cemetery likely served a proprietary church of a Late Saxon rural settlement. The cemetery was probably used for the whole of the local rural settlement population, spanning members of the local rural tenancy hierarchy (Cessford in Robb n.d.).

St Mary Clopton, West Cambridgeshire (TL 3010 4870; Site Code: CL3)

Selected for: human material

St Mary Clopton was also selected to provide a rural parish site, although the material available is limited.

Clopton is a deserted Medieval village (DMV) located c.19km southwest of Cambridge, c.10-11km equidistant between other studied sites of Gamlingay and Melbourn (see below). Clopton is likely to have been founded sometime between the 10th-11th centuries, declining in the late 15th-mid 16th century when the land was converted to sheep grazing (Cessford in Robb n.d.). It is not clear when the Church of St Mary was founded, but it was present by at least the late 12th

century. The church was rebuilt in 1352 and this remained until c.1749, even after the village was deserted. It is likely that most of the population of the village of Clopton would have been buried in the churchyard, representing the social strata of a rural village.

Excavations were carried out in the area by James Alexander, in association with Cambridge University, between 1960-1964 (Alexander 1968). Approximately 70 skeletons were excavated during this time, associated with the church of St Mary. Most of these were reburied, but some bones remain in the Duckworth Collection, University of Cambridge.

4.5.2.4 Other Cambridgeshire Sites (varying periods)

Trumpington Meadows, South Cambridgeshire (TL 439 539; Site Code: TRM10)

Selected for: human material

Human skeletons from Trumpington Meadows were selected to represent prehistoric, more specifically Neolithic, individuals from Cambridgeshire. Trumpington is located c.4km south of Cambridge. The site at Trumpington Meadows was excavated by the CAU in 2010-11. The excavations revealed multiple phases of activity and burial, including human skeletal remains inside a barrow structure, which was likely to have been founded in the early Neolithic (c.3762-3648 cal. BC) (Evans, Lucy, *et al.* 2018).

Hinxton Road, Duxford, South Cambridgeshire (TL 4805 4585; Site Code: DUXHR02)

Selected for: human material

Human skeletons from Hinxton Road, Duxford were selected to represent the Iron Age/Roman period in Cambridgeshire. Duxford is located c.11km southeast of modern Cambridge. The site to the west of Hinxton Road was excavated by CAM ARC (now Oxford Archaeology East) and Albion Archaeology in 2002 (Lyons 2011). Excavation revealed a rich and long-standing landscape of human activity, spanning from the Bronze Age to the Medieval and Post-Medieval periods. An Iron Age 'ritual' landscape was identified, with multiple burials. The earliest was an isolated crouched burial, dated to c.830-540 cal BC. An enclosed late Iron Age and Early Roman cemetery was also identified, containing 37-38 individuals dating to between c.100 BC and AD 200 (Lyons 2011, p. 118).

Vicar's Farm, West Cambridge (TL 43119 59060; Site Code: VIC99)

Selected for: human and terrestrial faunal material

Human skeletons from Vicar's Farm were selected to represent the Late Roman period in Cambridgeshire, faunal bone was also selected to provide a Roman faunal 'isotopic baseline'. Vicar's Farm (now part of the University of Cambridge West Cambridge Site) is located c.2km west of modern central Cambridge, although it would have only been c.1km from the Roman town in Cambridge. Vicar's Farm was excavated by the CAU in 1999-2000 and revealed a Roman settlement site (Evans and Lucas 2020). Human remains were found across the site, including a cremation cemetery in the Forecourt Area attributed to the phase spanning AD 80-180. A later enclosed inhumation cemetery was found in area D, attributed to the phase spanning AD 270-410. This comprised of 29 graves, with 30 individuals. Unfortunately, the skeletons were highly fragmentary (Dodwell 2001). Faunal bone was found across the site, with contemporary deposits to the inhumation cemetery found in the core settlement (area A) and the southern core extension (area B). Cattle dominated the Roman assemblage, with some potential ritual deposits (Clarke 2001).

Northstowe, South Cambridgeshire (TL 4029 6727; Site Code: NNS14)

Selected for: terrestrial faunal material

Faunal bone from the settlement site of Northstowe was selected to provide an Anglo-Saxon faunal 'isotopic baseline'. Northstowe is c.12km away from Edix Hill, the Anglo-Saxon cemetery sampled in this thesis (see below), and so may not be fully representative of their available diet, however, no suitable well-stratified Anglo-Saxon faunal material was available from Edix Hill. Northstowe is a new town development located c.11.5km northwest of modern central Cambridge. A substantial 'Phase 1' excavation covering 28.1 hectares was undertaken by the CAU in 2014-2015 (Collins 2016). Archaeological evidence from the Late Bronze Age/Early Iron Age to the Post-Medieval period were identified, with potential evidence of almost continuous occupation. There is evidence of an Early Saxon settlement near to Romano-British activity, although this site appears to have been abandoned, with a new Middle Saxon enclosure established a few hundred metres to the west. Over 16,000 fragments of animal bone were recovered from the Phase 1 excavations, of which 2648 were identified to species

(Rajkovača 2016). Most of the material (c.85%) was recovered from the Early to Middle Saxon periods, with a dominance of cattle.

Edix Hill (Barrington A), South Cambridgeshire (TL 37284 49714; Site Code: BAEH89-91)

Selected for: human material

Human skeletons from Edix Hill were selected to represent the Early Anglo-Saxon period in Cambridgeshire. Barrington is c.12km to the southwest of modern central Cambridge. It was known that an inhumation cemetery was located at Edix Hill since the late 19th century, but it was not extensively excavated until the Cambridge County Council's Archaeological Field Unit carried out works between 1989-1991 (Malim and Hines 1998). These excavations recovered human skeletal material representing at least 149 individuals from 115 graves, dating to between c. 6th-7th century, based on artefact typology (Malim and Hines 1998). Due in part to the large number of individuals recovered and the fact that the site has been thoroughly published (Geake 2000), the skeletal remains from Edix Hill are often cited- they have been used to illuminate chronology (e.g. Bayliss *et al.* 2013), burial practice (e.g. Williams 2006) (especially relating to non-adults (Buckberry 2000, Sayer 2014)) and health (e.g. Roberts and Cox 2003, Gamble 2011, Kendall *et al.* 2020) in the period.

Station Road, Gamlingay, South Cambridgeshire (TL 243 519; Site Code: HAT257)

Selected for: human material

Human skeletons from Station Road, Gamlingay were selected to represent the Mid-Late Saxon period in Cambridgeshire. Gamlingay is located c.26km west of modern central Cambridge, making it the most distant site sampled as part of this thesis, although skeletons from this period are rare and so these were the closest reasonably sized group available. Excavated in 2006 by Hertfordshire Archaeological Trust (now Archaeological Solutions) revealed a Middle Anglo-Saxon settlement, a cemetery containing c.110 burials and six marginal dispersed burials (Murray and McDonald 2006). New dating and phasing indicate that the dispersed burials are likely to date to the 8th or 9th centuries and the cemetery is likely to date to the 10th-11th centuries, meaning the burials were not strongly associated with the Middle Anglo-Saxon settlement (Cessford and Alexander in Robb n.d.). No church has been associated with the cemetery, therefore it is unknown what kind of population was buried at the cemetery, although it probably represents a rural community (Cessford in Robb n.d.).

Former Master's Lodge and Great Hall, Corpus Christi, Cambridge (TL 4487 5822; Site Code: CBG18)

Selected for: aquatic faunal material

Fish bone was selected from Corpus Christi College, Cambridge to represent part of the faunal 'isotopic baseline' for the Medieval town. As mentioned above, Corpus Christi is in the centre of modern Cambridge. Excavation was carried out at the College in 2018 by the CAU, primarily investigating the site of the 14th century Master's Lodge and Great Hall. A moderate fish bone was assemblage of 1954 fragments was recovered predominantly from layers dating to the early to mid-14th century, and a pit dating to the mid-16th century (Rajkovača 2018, Hamilton-Dyer unpub.).

Holy Trinity Church, Cambridge (TL 4498 5852; Site Code: HTC16)

Selected for: human material

Human bone was selected from Holy Trinity Church to represent the Post-Medieval period in Cambridge. Holy Trinity is an active Anglican church in the centre of modern Cambridge, located on the corner between St Mary's Street and Sidney Street. Excavations at Holy Trinity by the CAU in 2016-2017 revealed 20 inhumations (Newman 2018). Although the church building was constructed from the 12th century onwards, and so would also have been part of the Medieval landscape, the majority of the burials excavated are Post-Medieval. Seven burials dated to c.17th to 19th century and eight dated to 1833-55. The later burials were interred in brick-lined vaults and it has been possible to link these to records to hypothesise the identities of some of the individuals (Newman 2018).

4.5.2.5 Sites Previously Studied

A small number of archaeological sites in Cambridgeshire have been subject to previous isotope analysis. These include several sites which have been selected for this thesis: Hinxton Road, Duxford (Lyons 2011), Edix Hill (Barrington A) (Mays and Beavan 2012), the Hospital of St John (Price 2013) and St John's Triangle (Barrett *et al.* 2011). Other sites from central Cambridge were also included in Barrett *et al.* (2011): Cambridge Grand Arcade and Hostel Yard, Corpus Christi. Several sites have been analysed as part of MPhil theses at the University of Cambridge: The Babraham Institute (Friedman 2007), Grange Road Sewerage Extension,

King's Garden Hostel and St John's Christ's College Cricket Ground (all Cambridge) (Kulick 2010) and Water Lane, Melbourn (Hannah 2015, Hannah *et al.* 2018). Westfield Farm, Ely has also been investigated and comprises one of the only published isotope studies of a Cambridgeshire site to date (Lucy *et al.* 2009). For this thesis, it seemed logical to incorporate previous isotope data from the Cambridgeshire region into the primary dataset on a case-by-case basis. Much of the previous isotope analysis was carried out at the McDonald Institute, University of Cambridge, following the same protocols as this thesis (excluding Hinxton Road, Duxford and Edix Hill). Only data produced at the McDonald Institute was considered to be suitably comparable to incorporate with the primary thesis data. In addition, for carbon and nitrogen isotope analysis of human bone collagen, where stated, only samples which had been carried out on human rib (not long bone) were incorporated. These criteria ultimately excluded the data from Hinxton Road, Duxford, Edix Hill, Grange Road Sewerage Extension, King's Garden Hostel and St John's Christ's College Cricket Ground. To complement the site information above, short descriptions of the remaining additional sites are as follows:

The Babraham Institute (TL 50600 57000)

Selected for: human material

Babraham is located c.11km southeast of Cambridge. A Roman cemetery was excavated at the Babraham Institute by the CAU in 2006 (Timberlake *et al.* 2007). Excavations revealed human skeletal material of at least 42 individuals, as well as seven cremations. While the cremations appear to be earlier (late 1st to early 3rd century), the majority of the inhumation burials have been phased to the late 2nd to early 4th century (Timberlake *et al.* 2007) The site shows similarities in burial practice and chronology to Vicar's Farm, although it the inhumation cemetery was larger at Babraham (*ibid.*).

In 2007, an isotopic investigation of the late Roman skeletons was carried out, producing carbon and nitrogen isotope results for 26 rib collagen samples and 20 long bone collagen samples, as well as 24 carbonate carbon and oxygen isotope results from tooth enamel (Friedman 2007).

Water Lane, Melbourn (TL 38340 43960)

Selected for: human material

Melbourn is located c.17km southwest of Cambridge. The site at Water Lane was excavated in 2000 by Albion Archaeology, revealing 52 graves containing 59 individuals (Duncan *et al.* 2003). Based on artefactual and stratigraphical evidence, it is estimated that the cemetery was only in use for c.100 years, between c. AD 575 and c AD 675, making it slightly earlier than Edix Hill, c. 7km to the North.

As part of a comparison of Anglo-Saxon diet in the conversion period, Hannah (Hannah 2015, Hannah *et al.* 2018) analysed 51 individuals from Water Lane for carbon and nitrogen isotope ratios – 32 from rib collagen and 19 from various long bone collagen. Mays and Beavan (2012) had previously published carbon and nitrogen isotope results for nine individuals from Water Lane, but the samples were taken from long bones and processed at Iso-Trace New Zealand Limited, so are excluded.

Westfield Farm, Ely (TL 52600 79900)

Selected for: human material

Ely is located c. 27km northeast of Cambridge, making it the furthest site from Cambridge to be selected. An excavation by the CAU in 2006 exposed 15 graves, including a central foundation burial which may have been underneath a barrow. Grave goods indicate the burials date to the later 7th century and the group likely represents a high-status demographic, possibly related to the foundation of the first monastery in Ely (Newman 2007, Lucy *et al.* 2009).

Lucy *et al.* (2009) provides a detailed analysis of the 15 individuals excavated. Rib and femur samples were taken from all of the individuals for carbon and nitrogen isotope analysis. Tooth enamel samples from 14 of the 15 individuals were also analysed for carbonate carbon and oxygen isotope ratios.

Cambridge Grand Arcade (TL 45100 58300)

Selected for: aquatic faunal material

The Grand Arcade is located in central Cambridge, between St Andrew's Street, Downing Street and Corn Exchange Street. The main excavation of the area, prior to the building of the Grand Arcade shopping centre, was undertaken in 2006 by the CAU (Cessford 2007). In

relation to the landscape of High/Late Medieval Cambridge, the area would have been located just to the East of the Augustinian Friary and would have encompassed a portion of the 12th Century 'King's Ditch'. Similar to the Eastern Gate Hotel site, although much more densely packed, the main archaeological features of the area are c.20 narrow, long-standing 'burgage plots', which were established from the mid-11th century onwards (Cessford and Dickens 2019).

3697 fish bones from the Grand Arcade were identified to species or species group (Cessford and Dickens 2019, pp. 197–199). These were recovered from features dated from the 11th-19th century, although the majority were recovered from 14th century deposits (*ibid.*). Nine cod bones from 13/14th or 15th/16th century features were sampled for carbon and nitrogen isotope ratios as part of the study into medieval sea fishing by Barrett *et al.* (2011).

Hostel Yard, Corpus Christi Cambridge (TL 44820 58260)

Selected for: aquatic faunal material

As described above, Corpus Christi College is located in the centre of modern Cambridge. Hostel Yard was excavated in the grounds of Corpus Christi by the CAU in 2004 (Cessford 2005). Excavation revealed a deep stratigraphical sequence, with 11th and 12th-century quarry pits and domestic occupation from the 13th to 17th centuries. This included 1026 identified fish bones from the 14th and 16th century (Harland 2008), some of which were sampled for isotope analysis by Barret *et al.* (2011).

4.5.3 Individual Human Skeleton Selection

Chapter 2 illustrated that individual characteristics such as sex, age and social group were important factors that affected lived experience in the past, particularly in the High/Late Medieval period. Therefore, the sampling strategy for selecting individuals was primarily concerned with representing a cross-section of society, providing information about the populations of 'town' and 'rural' Cambridge in order to make observations and comparisons between different groups of people.

However, while it was deemed important to select a proportionate sample of males and females and those of various ages and social groups, it was decided that not all these factors could be examined in detail in the results. I decided that, while the experiences associated with stages of the lifecourse were an important aspect of Medieval life (Gilchrist 2012), the disjuncture between chronological, biological and social age (Gilchrist 2012, pp. 38–47), the large margins of error associated with estimating age from human skeletons (Chamberlain 2006, pp. 98–112), the uncertainty relating to 'turnover' of human bone collagen (Hedges *et al.* 2007) and the small sample sizes associated with breaking down skeletal populations by age category, meant that analysis of the data by detailed age stage was beyond the scope of this thesis and that the focus should be on sex and social groupings.

For carbon, nitrogen and oxygen isotope analysis, Sarah Inskip and I decided that the selection strategy should prioritise skeletons with good preservation and completeness, particularly those with key elements for optimal data collection (e.g. skull, teeth, pelvis) to maximise the amount of information gathered about each individual. For isotope analysis, I decided that the sampling strategy should prioritise adults (>18yr), to avoid inherent physiological complications in interpretation and comparison of non-adult bone collagen isotope values (Reynard and Tuross 2015). I decided that where possible, the skeletons sampled should proportionately reflect the available adult demography, so that the individuals chosen were potentially representative of the population of Cambridge at the time. However, analysis of non-adults (<18yr) was required for the 'After the Plague' project and so it was decided that the sampling would include a minority of non-adults. The aim was to ideally sample at least c.40 individuals per site, but most collections are not large enough to provide this.

For rib collagen carbon and nitrogen isotope analysis I decided that samples should be selected from individuals from all High/Late Medieval and longue durée sites to provide a large dataset through time. As sampling the longue durée sites is primarily to provide an approximate 'deeper time' context, it was not deemed necessary to sample dentine as well as ribs for all sites. Therefore, for dentine collagen carbon and nitrogen isotope analysis I decided that samples should only be selected from the High/Late Medieval sites as well as some Early Medieval sites, to capture potentially important transitions between the Early and High/Late Medieval periods. For enamel carbonate analysis, I decided that where possible, the same individuals as had been sampled for rib collagen carbon and nitrogen isotope analysis should be sampled to provide information about mobility throughout the longue durée.

For strontium isotope analysis, the sampling strategy was primarily determined by myself, with input from various members of the 'After the Plague' project. Due to the nature of the questions, the time-consuming nature of the lab work and the expense of strontium analysis, I decided that the strontium isotope analysis should predominantly focus on the High/Late Medieval sites. Next, I decided that the selection should be delayed to until most of the skeletons had undergone carbon, nitrogen and oxygen isotope analysis, as well as other osteological and scientific analysis. The aim was then to identify individuals who had also produced successful results for the other isotope analysis and to consult other members of the 'After the Plague' project as to potential individuals of interest, based on other analyses.

Sample selection for strontium isotope analysis often suffers from limited resources leading to preferential sampling of individuals who already display characteristics which may indicate they are 'atypical' or 'non-local,' e.g. unusual grave goods, unusual burial position, pathology (e.g. Roberts *et al.* 2013, Roffey *et al.* 2017, Moore *et al.* 2020). Whilst this approach is often inescapable in strontium-based research in bioarchaeology, this thesis aimed to select both 'atypical' individuals, as well as a good portion of individuals who looked 'typical' based on evidence from other areas of the project. This approach not only allows us to broaden our understanding of the general population of High/Late Medieval Cambridge but allows us to put the 'atypical' cases into a more solid local isotopic context. It is also a slightly different approach to many previous studies and may allow us to test the validity of 'cherry-picking' as an approach to strontium research.

The finalised criteria for selecting 'typical' individuals for strontium isotope analysis were (in approximate order of importance):

- High/Late Medieval sites only (except some individuals from Gamlingay and Edix Hill)
- Suitable tooth present
- Adult (>18yrs)
- Successful results for other isotope analyses, especially $\delta^{18}O$
- Representative sex ratio
- Good skeletal completeness/highlighted by 'After the Plague' as Gold priority (individuals with the most research potential)
- High aDNA coverage – individuals with coverage >0.05x which have the greatest potential for further genetic study

Several of these criteria also applied to the selection of 'atypical' individuals, e.g. only High/Late Medieval sites, suitable tooth present, successful results for other isotope analysis, but the specific criteria used to select 'atypical' individuals were as follows:

- Isotopic: individuals who were outliers within their population or noticeably unusual in their $\delta^{13}C$, $\delta^{15}N$ or $\delta^{18}O$ values (identified by the author)
- Genetic: individuals with distinctive mtDNA/autosomal data. Rare mtDNA haplotypes cannot necessarily be used as an indication of potential 'non-local' birth without further evidence, such as autosomal data. However, several individuals were identified at the time of strontium selection as having possible 'non-local' ancestry for various reasons (identified by Toomas Kivisild)
- Skeletal Activity Markers: individuals with unusual entheseal markers, which may indicate they were doing different activities to others in the population (identified by Sarah Inskip)
- Burial: individuals with unusual burial locations or positions or unusual grave goods (identified by Craig Cessford)
- Highlighted by 'After the Plague' for osteobiography (individuals selected as case studies)

Unfortunately, pathological data was not available to inform sample selection, although it is unlikely that any specific pathological disease found in Medieval Cambridge would be directly relevant to questions regarding mobility and migration anyway.

4.5.4 Human Skeletal Element Selection

The types of skeletal tissue to be targeted were decided by myself, based on suitability, availability and the elements chosen for comparable studies. For carbon and nitrogen isotope analysis, a multi-tissue approach was decided upon to provide high-resolution data and to analyse changes across an individuals' lifespan (following Sealy *et al.* 1995). To achieve this, I

decided that both bone and tooth dentine collagen should be sampled, to represent isotopic signatures during childhood/adolescence when the teeth were forming, as well as years before death, when the bone was turning over. For oxygen and strontium isotope analysis, I decided that only tooth enamel should be sampled as this is resistant to diagenetic change which can affect the reliability of the results (Budd *et al.* 2000, Hoppe *et al.* 2003, Zazzo *et al.* 2004). Macroscopically observable pathological lesions, e.g. osteomyelitis in bone; gross caries in teeth, should be avoided to reduce the destruction of pathological evidence but also because pathological bone growth and dental pathology may affect isotope results (Katzenberg and Lovell 1999, Olsen *et al.* 2014). Ideally, the aim was to sample each High/Late Medieval individual for all analyses, where possible.

4.5.4.1 Bone

I decided that ribs should be preferentially selected for carbon and nitrogen isotope analysis since they are an easy and minimally destructive element to sample, there are usually multiple available and they are often already fragmented, meaning they have limited future research potential. They are commonly sampled in archaeological isotope studies and so are the most directly comparable to other data. It is also assumed that rib bone is likely to 'turn over' more rapidly than denser bones, such as the femoral shaft, and so may represent an isotopic signature from the last few years before death (Hedges *et al.* 2007, Fahy *et al.* 2017, Matsubayashi and Tayasu 2019). For consistency and to avoid the destruction of potentially diagnostic features, e.g. rib head for pathology or rib counts, sternal rib end for aging, I decided that the rib midshaft should be preferentially sampled.

4.5.4.2 Teeth

To minimise the destruction of irreplaceable dental material, I decided that only one tooth per individual should be selected for isotope analysis. I decided to focus on second premolars (PM2) or second molars (M2) for three reasons. First, these teeth develop at a similar time, forming between approx. 2.5yr and 12.5yr (AlQahtani 2008). As this study aims to maximise the amount of data achieved from each tooth, a choice had to be made as to which teeth provide the most suitable age range for both the enamel and the dentine. I decided that PM2s or M2s would be most suitable as the enamel is formed between c. 2.5-7.5yr, the dentine begins

forming from c.5yr and the dentine root (from the enamel-dentine junction to the root tip) is formed between c.7.5-12.5yr (AlQahtani 2008) and so the enamel represents early to mid-childhood for mobility studies and the dentine represents middle childhood to adolescence for dietary studies. Importantly, the isotope values from these teeth should not be affected by any kind of childhood weaning effect. Second, choosing a combination of PM2s or M2s increases choice when sampling, allowing potential for eight suitable teeth per individual. Third, these teeth are the preferred choice in many archaeological isotope studies and so are most comparable to previous data.

For simplicity of data comparisons, if suitable ribs, PM2 or M2s are not available it was decided that alternative tissues would not be sampled, even if this meant the individual was left out of the cohort.

4.5.5 Faunal Isotopic Baseline

As discussed in Chapter 3, fluctuations in local faunal carbon and nitrogen isotope values can have serious implications for analysis of human isotope values and so sampling faunal material to provide information about the local 'isotopic baseline' is recommended (e.g. Bownes *et al.* 2018). As there is currently no known isotope data for terrestrial fauna in Cambridge, and very little for aquatic fauna (except for Barrett *et al.* 2011), I decided that commonly consumed terrestrial and aquatic fauna should be sampled for isotope analysis from all time periods that have been sampled for human isotope analysis, where possible.

4.6 Statistical Approach

In 2016, the American Statistical Association released a statement on statistical significance and *p*-values in scientific research (Wasserstein and Lazar 2016). This statement addressed decades of ongoing concern regarding the misuse and misinterpretation of *p*-values and set out several key principles regarding the use and reporting of the values, concluding that 'no single index should substitute for scientific reasoning' (Wasserstein and Lazar 2016, p. 132). Following this, a special edition of 'The American Statistician' discussed the future of research beyond 'p=<0.05', categorically advising against the use of the phrase 'statistically significant' (Wasserstein *et al.* 2019). In light of these publications and the general trend in archaeological

science to improve approaches to large data sets, this thesis will aim to embrace these principles and while incorporating some commonly-used statistical analysis, the focus will be on exploratory methods, such as those seen in the fields of ecology (e.g. Zuur *et al.* 2010).

4.7 Data Archiving and Dissemination

The FAIR principles for scientific data management and stewardship – Findability, Accessibility, Interoperability and Reusability - are becoming increasingly important, particularly in fields which are collecting quantitative data (Wilkinson *et al.* 2016). This thesis aims to honour these principles, with help from recent guidelines produced by the PARTHENOS project (Hollander *et al.* 2019), by striving to make the data produced as user-friendly and accessible as is currently possible in the field. At present, there is no standardised way to archive archaeological isotope data and no satisfactory centralised repository for isotope data generated in the UK, with initiatives like ISOARCH ('a web-based database of isotopic data for bioarchaeological samples from the Greco-Roman world and its margins') (Salesse *et al.* 2018) being limited to specific time periods, or IsoMemo (' a Big Data initiative bringing together isotopic data from archaeology, ecology, and environmental & life sciences') (IsoMemo.com 2016) which is still under development. The need for a global, centralised web-accessible database has been recognised and a project is currently working to create an 'IsoBank', which could revolutionise isotopic research, although it is unlikely to be completed for some years (Pauli *et al.*, 2017; *NSF Award Search: Award#1759937 - Collaborative Research: ABI Development: IsoBank: A centralised repository for isotopic data*, 2018). Following Wellcome Trust requirements, the data produced in this thesis will be readily available for future researchers, either via online repositories for archaeological data (e.g. Apollo-Cambridge University), through the 'After the Plague' project monograph, which is due to be published after 2020, or through open-access journal articles.



5. Materials and Methods

Following the research design (Chapter 4), this chapter discusses the selection and categorisation of the new human and faunal materials sampled, the methods used to produce new isotope data and the methods used to analyse the data. The isotope analyses employed are separated into three methodologies: carbon (C) and nitrogen (N) in bone and tooth dentine collagen, carbon and oxygen (O) in tooth enamel carbonate and strontium (Sr) in tooth enamel.

5.1 Sample Selection: Human

5.1.1 Categories Used for Human Skeletal Material

5.1.1.1 Sample Categorisation

All human skeletons analysed as part of the 'After the Plague' project were assigned a unique Project Skeleton Number (PSN) to avoid confusion of repeated skeleton or context numbers. For ease, PSNs have been used in this thesis. In cases where a PSN was not given, such as for comparative data, the skeleton number was used. All identifying numbers for skeletons can be found in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053).

5.1.1.2 Sex Categorisation

Estimation of sex for all adult individuals was determined prior to sampling through macroscopic observations of skeletal traits on the pelvis and the skull by Sarah Inskip (in Robb n.d., Inskip *et al.* 2019). Genetic sex was also determined for a large proportion of the non-adult and adult skeletal material by Christiana Scheib using a shotgun approach (*ibid.*). Individuals were assigned to female, male or unknown sex categories. Where an individual had both a

macroscopic and genetic sex determination, genetic sex took precedent. For previously published adult individuals with isotope data, published sex estimations were recategorized to female, male or unknown (e.g. ?female was assigned to female), to allow for maximum comparable data.

5.1.1.3 Age Categorisation

Age estimation for all individuals was carried out prior to sampling by Sarah Inskip using macroscopic methods based on the dentition (Moorrees *et al.* 1963, Brothwell 1981, Ubelaker 1987, Smith 1991), non-adult skeletal development (Scheuer and Black 2000) and adult skeletal traits in the ribs, pelvis, and clavicle (İşcan *et al.* 1984, 1985, Brooks and Suchey 1990, Buckberry and Chamberlain 2002, Falys and Prangle 2015). All skeletal material was assigned to Bradford Biological Anthropology Research Centre (BARC) ageing categories (Table 5). Skeletons were also assigned to broader age categories for lower resolution analysis (Table 6). The distinction between non-adults and adults was defined at 18 years. This is based on a) the delineation of the adolescent/young adult BARC ageing categories and b) mostly complete skeletal/biological maturity, meaning less physiological complications for interpreting isotope results from bone. It is acknowledged that choosing 18 years to define adulthood is an artificial construct and is unlikely to reflect social perceptions of adulthood and childhood in the past. Previously published individuals with isotope data were only categorised to adult/non-adult and not to the BARC age categories as it was deemed high-resolution age data was not needed for these sites.

Category	**Age Group**	**Age Range**
0	Non-Adult (Unknown Age)	<18 years
1	Foetus	Under 40 weeks
2	Neonate	Birth-1 month
3	Infant	1 month-12 months
4	Early Childhood	1-6 years
5	Late Childhood	7-12 years
6	Adolescent	13-17 years
7	Young Adult	18-25 years
8	Young Middle Adult	26-35 years
9	Old Middle Adult	36-45 years
10	Mature Adult	46-59 years
11	Old Adult	60+ years
12	Adult (Unknown Age)	>18 years

Table 5: Specific age categories used for skeletal analysis, adapted from the Biological Anthropology Research Centre (BARC) Ageing Categories

Broad Age Group	Age Range
Non-Adult	0-17 years
Young Adult	18-25 years
Middle Adult	26-45 years
Old Adult	45+ years

Table 6: Broad age categories used for skeletal analysis

5.1.1.4 Site Subgroup and Social Group Categorisation

Individuals were assigned to site subgroups by Craig Cessford, based on site chronologies and discrete burial contexts. Broad social groups were assigned by Sarah Inskip, John Robb and Craig Cessford. These subgroups were designed to allow comparisons based on social characteristics, e.g. urban/rural, adult/non-adult, female/male. Due to burial with buckles, Friars could also be distinguished from lay individuals (Cessford in Robb n.d.).

5.1.1.5 Date Categorisation

Dating of the sites and the individuals sampled was determined by Craig Cessford and Craig Alexander using radiocarbon dating, Bayesian modelling, textual sources, archaeological stratigraphy, burial truncations and artefactual evidence. Sites were assigned broad periods of use and site subgroups were identified for sites with distinctive phases of burial. The relative chronologies of the site subgroups can be seen in Figure 21. Likely date ranges for the death and burial of Middle Anglo-Saxon to Post-Medieval individuals were modelled and these were used to calculate individual estimated median death dates (Cessford and Alexander in Robb n.d.). Where possible, it was determined whether High/Late Medieval individuals were likely to have died pre- or post-Black Death (1349-50) and the Medieval century in which they were likely to have died.

For analysis, all skeletal material used in this thesis was assigned to a chronological period based on British archaeological and cultural periods defined by Historic England (2013), with more specific divisions for the Medieval periods (Table 7, Figure 21, see Section 4.4 for further discussion). If the date ranges for a site or individual human/faunal sample spanned two specific periods, then it was assigned to the period with the greatest overlap/best cultural fit. If their dating was very broad and uncharacteristic, then they were only assigned to a general cultural period, but not a specific sub-period.

Category	British Archaeological/ Cultural Period	Category	Subdivided Archaeological/ Cultural Period	Approx. Start Date	Approx. End Date
1	Neolithic	1	Neolithic	-4000	-2200
2	Bronze Age	2	Bronze Age	-2600	-700
3	Iron Age	3	Iron Age	-800	43
4	Roman	4	Roman	43	410
5	Early Medieval	5	Early Anglo-Saxon	410	660
		6	Middle Anglo-Saxon	660	900
		7	Late Anglo-Saxon	900	1066
6	High/Late Medieval	8	High Medieval	1066	1272
		9	Late Medieval	1272	1540
7	Post-Medieval	10	Post-Medieval	1540	1901

Table 7: Broad and specific British archaeological/cultural periods used (BC/AD), based on Historic England period list (2013)

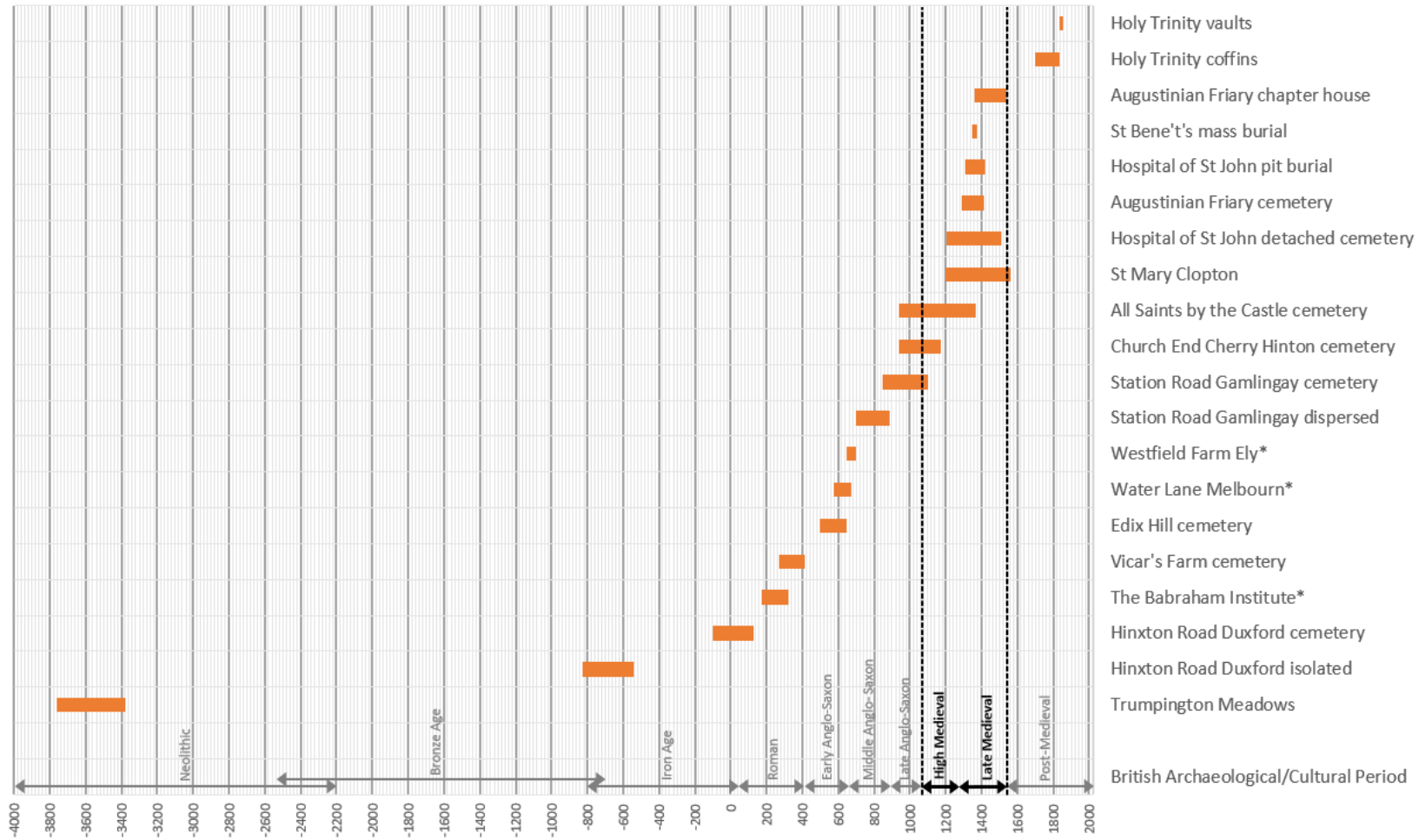


Figure 21: Timeline (BC/AD) of all Cambridgeshire sites with human isotope data discussed in this thesis (by site subgroup).

** = sites with previous isotope analysis results: Westfield Farm Ely (Lucy et al. 2009), Water Lane Melbourn (Hannah 2015, Hannah et al. 2018), The Babraham Institute (Friedman 2007). High/Late Medieval period highlighted with vertical dashed lines. See Table 8 below for approx. number of skeletons excavated and number of samples taken for isotope analysis.*

5.1.2 Human Sample Summary by Site Subgroup

Table 8 provides a summary of the sites and site subgroups sampled for human skeletal material as part of this thesis (previously studied sites not included here), including approximately how many skeletons were excavated and how many were sampled for various isotope analyses. The analysis of some samples from Edix Hill was shared with University of Cambridge PhD student Samantha Leggett as part of a PhD investigating the Anglo-Saxon period.

Site	**Site Subgroup**	**Site Code**	**Approx. Date Range of Skeletons Analysed (as given in report)**	**Assigned British Archaeological/Cultural Period**	**Site Type**	**Approx. Nr of Skeletons Excavated**	**Skeletons Sampled for Dentine C&N**	**Skeletons Sampled for Bone C&N**	**Skeletons Sampled for Enamel O&C**	**Skeletons Sampled for Enamel Sr**
Trumpington Meadows	*Trumpington Meadows*	TRM10	c.3762-3648 BC	Neolithic	Barrow burials	4	0	3	0	0
Hinxton Road Duxford	*Hinxton Road Duxford isolated*	DUXHR02	827-540 BC	Iron Age	Crouched burial	1	0	1	1	0
Hinxton Road Duxford	*Hinxton Road Duxford cemetery*	DUXHR02	100 BC-AD 125	Roman	Enclosed cemetery	38	0	21	16	0
Vicar's Farm	*Vicar's Farm cemetery*	VIC99	AD 270-410	Late Roman	Enclosed cemetery	30	0	17	15	0
Edix Hill/ Barrington A	*Edix Hill cemetery*	BAEH89-91	AD 500-650	Early Saxon	Cemetery	c.149	38*	44*	39*	2*
Station Road Gamlingay	*Station Road Gamlingay dispersed*	HAT257	AD 701-889	Mid Saxon	Dispersed single burials	6	1	0	1	1
Station Road, Gamlingay	*Station Road, Gamlingay cemetery*	HAT257	AD 850-1100	Late Saxon	Cemetery	110	26	35	25	18

Site	Site Subgroup	Site Code	Approx. Date Range of Skeletons Analysed (as given in report)	Assigned British Archaeological/Cultural Period	Site Type	Approx. Nr of Skeletons Excavated	Skeletons Sampled for Dentine C&N	Skeletons Sampled for Bone C&N	Skeletons Sampled for Enamel O&C	Skeletons Sampled for Enamel Sr
Church End, Cherry Hinton	*Church End, Cherry Hinton cemetery*	HAT358/1	AD 940-1170	High Medieval	Rural parish church cemetery	c.670	40	47	40	28
All Saints by the Castle/ Comet Place	*All Saints by the Castle cemetery*	CP73	AD 940-1365	High/Late Medieval	Town parish church cemetery	210	31	43	34	23
St Mary, Clopton	*St Mary, Clopton*	CL3	AD 1200-1561	Late Medieval	Rural parish church cemetery	c.70	12	13	12	11
Hospital of St John the Evangelist	*Hospital of St John detached cemetery*	JDS10	AD 1200-1511	Late Medieval	Town monastic hospital cemetery	c.400	55	52	83	50
New Museums Site/ Augustinian Friary	*Augustinian Friary cemetery*	NRB16	AD 1290-1413	Late Medieval	Town Friary cemetery	32	16	23	17	12
Hospital of St John the Evangelist	*Hospital of St John pit*	JDS10	AD 1312-1419	Late Medieval	Pit burial	4	1	4	1	1
St Bene't's/ Hostel Yard, Corpus Christi	*St Bene't's mass burial*	HYC05	AD 1348-1377	Late Medieval	Town mass grave	5	4	0	4	4
New Museums Site/ Augustinian Friary	*Augustinian Friary chapter house*	NRB16	AD 1360-1538	Late Medieval	Chapter House burials	6	4	5	4	4
Holy Trinity Church	*Holy Trinity Coffins*	HTC16	AD 1700-1833	Post-Medieval	Town church cemetery	7	0	3	1	0
Holy Trinity Church	*Holy Trinity Vaults*	HTC16	AD 1833-1855	Post-Medieval	Town church vault	8	0	7	3	0

Site	Site Subgroup	Site Code	Approx. Date Range of Skeletons Analysed (as given in report)	Assigned British Archaeological/Cultural Period	Site Type	Approx. Nr of Skeletons Excavated	Skeletons Sampled for Dentine C&N	Skeletons Sampled for Bone C&N	Skeletons Sampled for Enamel O&C	Skeletons Sampled for Enamel Sr
	Total High/Late Medieval Individuals Sampled						**162**	**183**	**195**	**138**
	Total Individuals Sampled						**227**	**314**	**296**	**159**

*Table 8: Summary of site subgroups and number of individuals sampled for isotope analysis as part of this thesis. High/Late Medieval sites highlighted in grey. * = Samples run in conjunction with S.A.Leggett*

5.1.3 Individual Human Skeleton Selection

For carbon, nitrogen and oxygen isotope analysis, Sarah Inskip and I selected individuals to provide a good representation of sex, age and date categories from all High/Late Medieval and longue durée sites, where possible. Individuals with good preservation and completeness, particularly the availability of key elements for optimal data collection (e.g. skull, teeth, pelvis) were prioritised. Some collections did not meet the above criteria, but it was deemed that the skeletons should be sampled regardless, e.g. the skeletal material from Vicar's Farm was fragmentary and poorly preserved but was the only Roman material available at the time of data collection. At St Bene't's, only four skulls were recovered, with no post-cranial elements but the importance of their context justified further investigation despite the limited skeletal material.

For strontium isotope analysis, a relatively complex set of selection criteria was followed (Section 4.5.3). The individuals sampled were primarily selected from the High/Late Medieval sites only (except for a few individuals from Gamlingay and Edix Hill), and those who had also been selected for carbon, nitrogen and oxygen isotope analysis were prioritised. As above, a majority of the individuals were selected to provide a good representation of sex and age categories, but several were selected based on 'atypical' attributes identified through previous isotopic, genetic, skeletal and archaeological criteria, although some of these changed after Sr sampling, e.g. no longer interesting genetically after re-sequencing (see Table 9 for list of attributes).

Site	PSN	Specific Strontium Selection Criteria
Edix Hill/ Barrington A	550	High aDNA coverage; burial: unusual burial type; C, N & O isotope results
	573	High aDNA coverage; burial: unusual burial type; C, N & O isotope results
Station Road, Gamlingay	810	aDNA: mtDNA related to PSN 827; C, N & O isotope results
	813	High aDNA coverage, highest O isotope value from Gamlingay; C, N & O isotope results
	820	Lowest O isotope value from Gamlingay; C, N & O isotope results
	827	High aDNA coverage, aDNA: mtDNA related to PSN 810; C, N & O isotope results
Church End, Cherry Hinton	906	Lowest O isotope value from Cherry Hinton, high N isotope value; C, N & O isotope results
	911	ATP osteobiography character; C, N & O isotope results
	933	Second highest O isotope value from Cherry Hinton; C, N & O isotope results
	940	Skeleton: unusual facial morphology; C, N & O isotope results
	942	Low N isotope value from Cherry Hinton; C, N & O isotope results
	952	High N isotope value; C, N & O isotope results
	953	Highest O isotope value from Cherry Hinton; C, N & O isotope results
The Hospital of St John the Evangelist	62	High aDNA coverage; general request from S.Inskip; C, N & O isotope results; ATP gold priority
	65	High aDNA coverage; aDNA: possible autosomal outlier (at time of sampling); C, N & O isotope results; ATP gold priority
	91	High aDNA coverage; second lowest O isotope value from Hospital; C, N & O isotope results
	92	High aDNA coverage; aDNA: possible interesting autosomal DNA (at time of sampling); low C&N isotope values; highest O isotope value from Hospital; C, N & O isotope results; ATP gold priority
	115	Skeleton: possible interesting activity patterns; C, N & O isotope results; ATP gold priority
	203	High C&N isotope values
	259	High aDNA coverage; aDNA: possible autosomal outlier (at time of sampling); C, N & O isotope results; ATP gold priority
	264	High aDNA coverage; high N isotope values; C, N & O isotope results; ATP gold priority
	265	Skeleton: possible interesting activity patterns; C, N & O isotope results; ATP gold priority
	331	Skeleton: possible interesting activity patterns; C, N & O isotope results; ATP gold priority
	332	High aDNA coverage; aDNA: possible interesting autosomal DNA (at time of sampling); C, N & O isotope results; ATP gold priority
	335	High aDNA coverage; C, N & O isotope results; ATP osteobiography; ATP gold priority
	356	C, N & O isotope results; ATP osteobiography; ATP gold priority
	357	High aDNA coverage; aDNA: possible autosomal outlier (at time of sampling); C, N & O isotope results; ATP gold priority
New Museums Site/ Augustinian Friary	500	aDNA: female child in Friary; C, N & O isotope results
	502	High aDNA coverage; aDNA: possible interesting mtDNA (at time of sampling); C, N & O isotope results
	509	High aDNA coverage; aDNA: possibly related to PSN 515; High C&N isotope results; ATP osteobiography character; C, N & O isotope results
	513	ATP osteobiography character; C, N & O isotope results

	515	aDNA: possibly related to PSN 509; C, N & O isotope results
	524	Burial: Parisian buckle; C, N & O isotope results

Table 9: Specific selection criteria for certain individuals targeted for Sr isotope analysis. Some criteria have changed since selection due to further analysis (predominantly aDNA results)

5.1.4 Human Skeletal Element Selection

5.1.4.1 Bone

I primarily selected the rib midshaft for collagen carbon and nitrogen isotope analysis. Macroscopically observable pathological bone was avoided.

5.1.4.2 Teeth

Only one tooth per individual was selected for isotope analysis. Second premolars (PM2) or second molars (M2) were targeted, with a preference for molars as they provided more material.

Areas of macroscopically observable pathological lesions, particularly gross carious lesions, were avoided during sampling. Teeth with linear enamel hypoplasia (LEH) were generally avoided. However, many teeth in one individual's dentition can be affected with LEH and so sampling teeth with defects was sometimes inescapable. Where possible, large cracks and 'chalky' areas of enamel were also avoided, but in some cases, the lack of available enamel and the size of the sample needed necessitated sampling of sub-optimal enamel.

Sampling of each type of dental material (enamel, dentine) was carried out logically and sequentially so that the most information possible could be obtained from a single tooth. Figure 22 summarises how single and multi-rooted teeth were divided for various isotope (and sometimes aDNA) analyses (see Figure 24 for order of sampling). For dentine collagen carbon and nitrogen isotope analysis, the tooth root was cut as close to the enamel-dentine junction (EDJ) as possible. For double rooted teeth, only one root was taken for analysis. For enamel carbonate carbon and oxygen isotope analysis, tooth enamel powder was drilled from the vertical sides of the tooth crown in a longitudinal pattern. As it represents the earliest stage of development, as well as being the most potentially informative for osteological studies, the occlusal surface of the crown was avoided. For enamel strontium isotope analysis, the vertical sides of the crowns were targeted, avoiding the occlusal surface of the crown and the thinnest

part of the enamel towards the EDJ. However, sampling suitably sized pieces of enamel was very difficult and, in some cases, sampling the occlusal surface was unavoidable. It is accepted that this means that the samples will not represent exactly the same stage of development, but an average over the development of the enamel.

For some individuals, only one tooth was available for all analyses, including aDNA. aDNA analysis was prioritised and sampling for aDNA occurred first to avoid further contamination. If analysis was shared, multi-rooted teeth were preferred as they are generally larger and easier to divide. However, due to sampling restrictions, in some cases (particularly at All Saints by the Castle/Comet Place), only single-rooted teeth were available. For these, approximately 1/3 of the tooth root (distal tip) was taken for aDNA and the remaining root was measured to allow for an approximation of the age range represented, and then cut at the EDJ as described above for collagen carbon and nitrogen isotope analysis.

Following good practice for destructive sampling, efforts were made to preserve High/Late Medieval material for future incremental dentine collagen carbon and nitrogen isotope analysis, e.g. method two in Beaumont *et al.* (2013), to allow the potential to investigate lifecourse further. This involved preserving at least half of the full dentine profile of a tooth. This was relatively simple for multi-rooted teeth as usually at least one root remained after sampling for bulk collagen carbon and nitrogen isotopes but was more problematic for single-rooted teeth. Several methods were tried but the most effective solution involved taking enamel samples for oxygen and strontium isotope analysis, removing the rest of the enamel, demineralising the dentine of the whole tooth, slicing the whole tooth in half longitudinally with a scalpel, gelatinising one half of the dentine (from EDJ to tip only) for bulk collagen carbon and nitrogen and storing the rest of the tooth dentine in distilled water for future research. However, this method is not recommended if samples are not going to be used for incremental sampling within a few months, as samples can go mouldy.

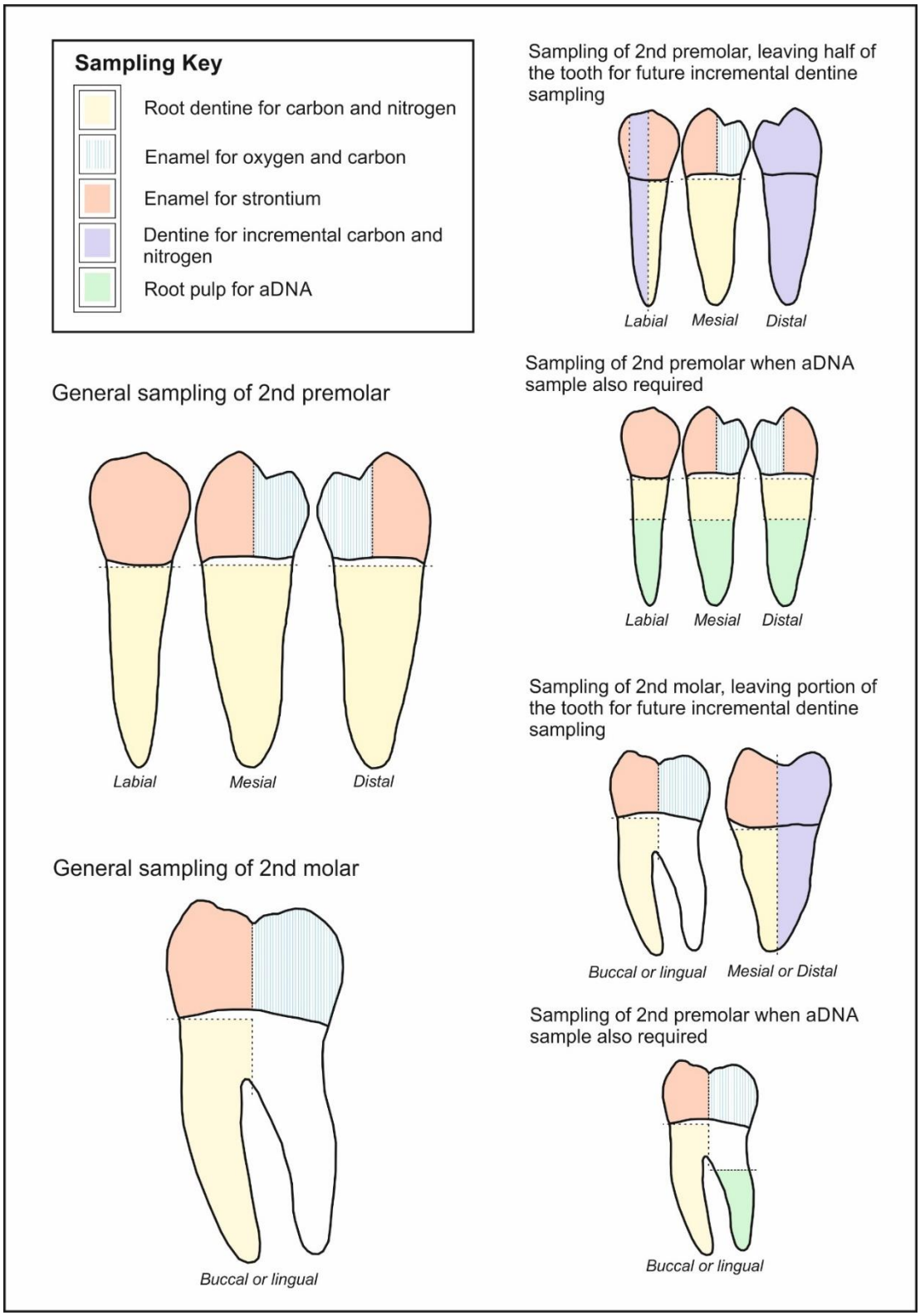


Figure 22: Diagrams illustrating how teeth were divided for analyses. Order of analyses depended upon number of analyses required per tooth – see Figure 24 for flowchart of processes. aDNA analysis always took priority to avoid further contamination

5.2 Sample Selection: Faunal

5.2.1 Terrestrial Fauna Sample Summary by Site

Table 10 provides a summary of the sites sampled for terrestrial faunal skeletal material. At Vicar's Farm, one cow bone taken for sampling was re-identified as a horse, however, as very little Iron Age material was available, it was sampled as well.

Site	Site Code	Approx. Date Range of Material Analysed (as given in report)	Assigned British Archaeological/ Cultural Period	Cow	Chicken	Sheep/Goat	Pigs
Vicar's Farm	VIC99	Iron Age	Iron Age	1 (horse)	0	1	0
		Iron Age/Roman	Iron Age	1	0	1	0
		Roman	Roman	10	3	10	7
Northstowe	NNS14	Early Saxon	Early Saxon	5	5	5	5
		Middle Saxon (1&2)	Middle Saxon	5	2	6	6
St John's Triangle	SJT07	c.AD 900-1200	Late Anglo-Saxon	5	5	5	5
		c.AD 1200-1350	Late Medieval	4	5	5	5
		c.AD 1350-1500	Late Medieval	6	5	5	5
		c.AD 1500-1751	Post-Medieval	5	5	5	5
New Museums Site	NRB16	c.AD 1050-1200	High Medieval	5	1	5	5
		c.AD 1200-1337	Late Medieval	10	10	10	10
		c.AD 1538-1545	Post-Medieval	2	2	2	2
		c.AD 1580-1763	Post-Medieval	1	1	1	1
Total Domestic Fauna Sampled				**60**	**44**	**61**	**56**

Table 10: Summary of sites and number of terrestrial faunal bones sampled for collagen carbon and nitrogen isotope analysis as part of this thesis. High/Late Medieval contexts highlighted in grey.

5.2.2 Terrestrial Fauna Selection

As the purpose of the faunal samples is to provide information about diet and variability in the isotopic baseline, the domesticated species of cow, sheep/goat, pig and chicken/domestic fowl were preferentially selected as they were the most commonly consumed in the High/Late Medieval period (see Chapter 2) as well as the longue durée. They are also relatively abundant in archaeological deposits and are comparable data for these species from similar studies is available.

5.2.3 Terrestrial Fauna Skeletal Element Selection

To ensure that the same animal was not sampled twice, only one bone per species per context was chosen. Juvenile bone and pathological bone were avoided where possible. An effort was made to select similar elements from each species, with a preference for tarsals and metapodials as they are identifiable to species, robust (so preserve well) and abundant as there are multiple per animal. However, this was not always possible, and in these cases, any available bone that was robustly identified to species was taken. Further details, including the elements sampled, are included in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053).

I chose the samples to give a good representation of species across time periods. However, as I am not a specialist in identifying faunal bone, almost all faunal samples were selected either with the assistance of Vida Rajkovača or Dan Sharman, faunal bone specialists at the Cambridge Archaeological Unit. Faunal remains from Vicar's Farm (VIC99), were selected by myself and checked by Sarah Inskip.

5.2.4 Aquatic Fauna Sample Summary by Site

Table 11 provides a summary of the sites sampled for aquatic faunal skeletal material.

Site	Site Code	Approx. Date Range of Material Analysed (as given in report)	Assigned British Archaeological/Cultural Period	Cod	Herring	Ling	Flatfish	Cyprinid	Pike	Eel
Eastern Gate Hotel Site	EGN12	c.AD 1200-1538	High/Late Medieval	7	4	1	1	4	1	2
Former Master's Lodge and Great Hall, Corpus Christi	CBG18	AD 14th-16th	Late Medieval	1	0	1	2	0	0	0
Total Fish Sampled				**8**	**4**	**2**	**3**	**4**	**1**	**2**

Table 11: Summary of sites and number of fish bones sampled for collagen carbon and nitrogen isotope analysis as part of this thesis

5.2.5 Aquatic Fauna Selection

As the purpose of aquatic faunal samples is to provide information about diet and the variability in the aquatic isotopic baseline, I targeted both riverine and marine fish species for sampling. Cod, herring, ling and flatfish were selected to represent marine fish while cyprinids and pike represented freshwater fish. Eels were also sampled. The aim was to target fish that were commonly consumed in the High/Late Medieval period, but the selection was restricted by the small amount of appropriately dated material available.

5.2.6 Aquatic Fauna Skeletal Element Selection

The excavated fish bone available for this study was very low in volume. In most cases, many bones per species per context had to be combined and it was not possible to guarantee that the bones all came from the same fish. Where possible, only the same type of bone was combined, e.g. vertebrae. Pre-caudal and post-caudal elements were never combined. Further details, including elements sampled, can be found in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053).

Samples were identified by Sheila Hamilton-Dyer, a freelance fish bone specialist. As the volume of bone was so small, almost all contexts where there were bones that could be identified to species and where the amount of bone was above 1g, were selected for isotope analysis. This could mean that some of the contexts were less secure or less well dated than the terrestrial fauna bone samples.

5.3 Methodology for Isotope Analysis

This section will describe the methods used for each type of isotope analysis. The methodologies used in this thesis are described in detail in the hope that they will be fully reproducible. Images taken during laboratory work for this thesis have been used to illustrate the stages. See Appendix VII for laboratory standard operating procedures (SOPs).

5.3.1 Methodology Flowcharts

Summary flowcharts have been created to show the general processes and the order in which they were undertaken (Figure 23 & Figure 24).

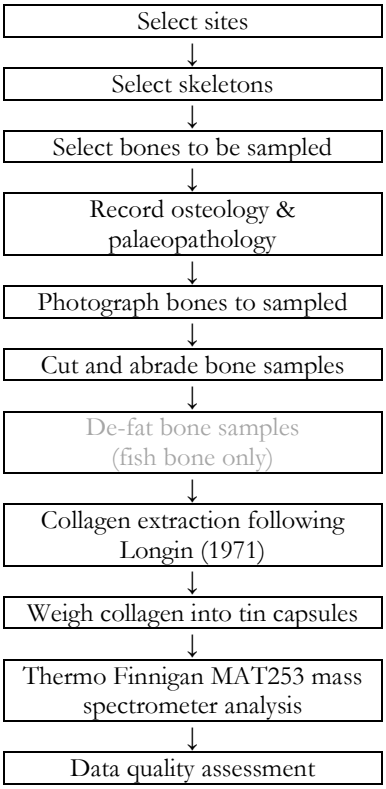


Figure 23: Flowchart summarising processes involved in bone collagen carbon and nitrogen isotope analysis

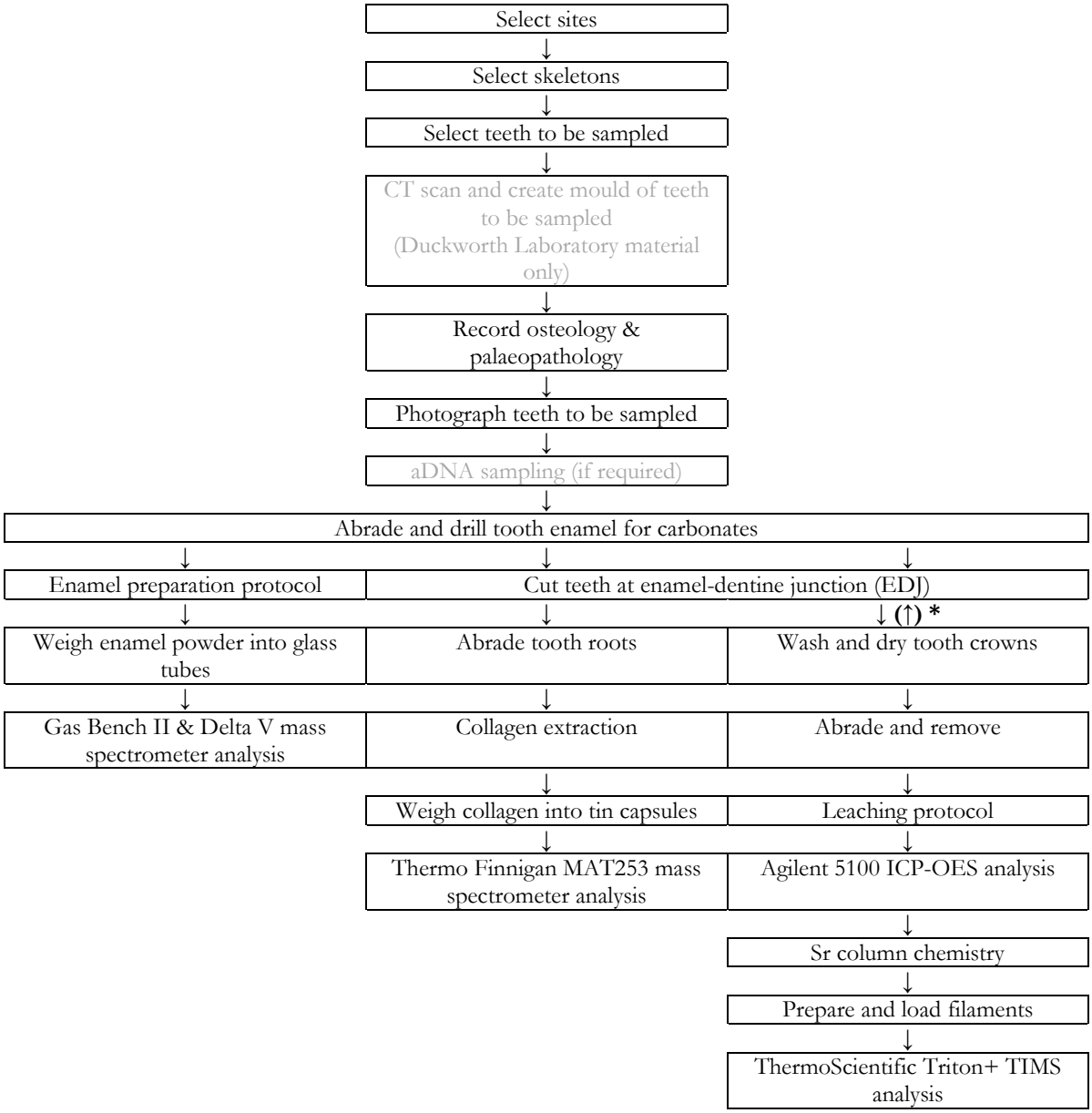


Figure 24: Flowchart summarising processes involved in various isotope analyses of teeth

* In some cases, due equipment availability etc., the order of processes had to be changed and teeth were not cut at the EDJ before being washed and dried for strontium isotope analysis. In these instances, the dentine was exposed to multiple rinses with ultrapure water and then temperatures of up to 50°C in the oven before being cut and abraded for collagen extraction.

5.3.2 Collagen Carbon and Nitrogen Isotope Analysis Methodology

Sampling and preparation of all collagen samples was carried out in the Dorothy Garrod Laboratory, McDonald Institute, University of Cambridge, following lab protocols (see Appendix VII) after training from Tamsin O'Connell, Catherine Kneale and Emma Lightfoot.

5.3.2.1 Sample Preparation

For human and terrestrial faunal bone, approximately 500mg of bone was cut using a hand-held Dremel drill with a diamond-tipped cutting wheel in a dust extraction hood. The bone surface was then abraded using a precision sandblaster to remove surface dirt and contaminants (Figure 25). For human dentine, the process was the same as above, except tooth roots yield less material so only c.300-400mg of root dentine was typically sampled. Fish bones above 500mg were subsampled - approximately 500mg of bone was removed using a hand-held Dremel drill and sandblasted as above. Fish bones that weighed up to 500mg were not subsampled and only those large enough to physically handle were abraded using the sandblaster. Small bones were not sandblasted, but excess dirt was removed manually with a toothbrush and water. Fish bones were then manually crushed using an agate pestle and mortar to allow for de-fatting stage (see below).

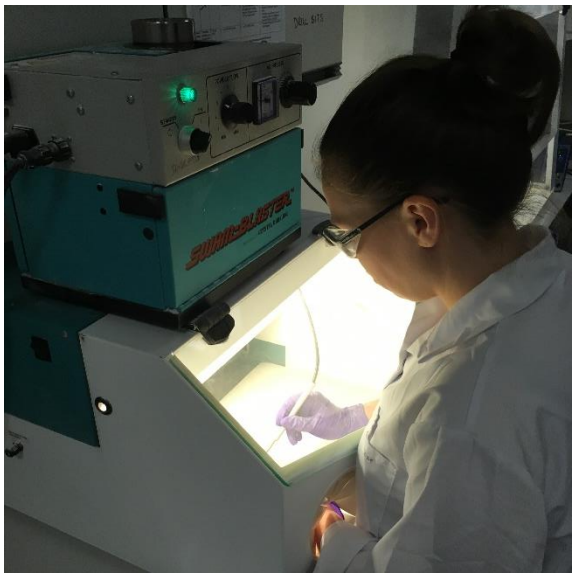


Figure 25: The author sandblasting bone samples to remove surface contamination

5.3.2.2 Collagen Extraction: Human Bone and Dentine and Terrestrial Faunal Bone

Collagen for carbon and nitrogen isotope analysis was extracted using a modified version of the Longin method (Longin 1971, Collins and Galley 1998, Richards and Hedges 1999). Based on available lab space, up to 40 samples could be processed at a time for collagen extraction. Firstly, the mineral content was removed by placing the samples into pre-weighed glass test tubes and adding approximately 8ml 0.5M aq. hydrochloric acid (HCl) (Figure 26). The samples were shaken twice a day and 0.5M hydrochloric acid replaced as appropriate (c. every 48hr) until full demineralisation. Demineralised samples were rinsed three times with distilled water to remove the acid. When all samples were demineralised, approximately 8ml pH 3.0 water was added. The samples were then heated in an oven in capped tubes for 48hr at 75°C until gelatinised.

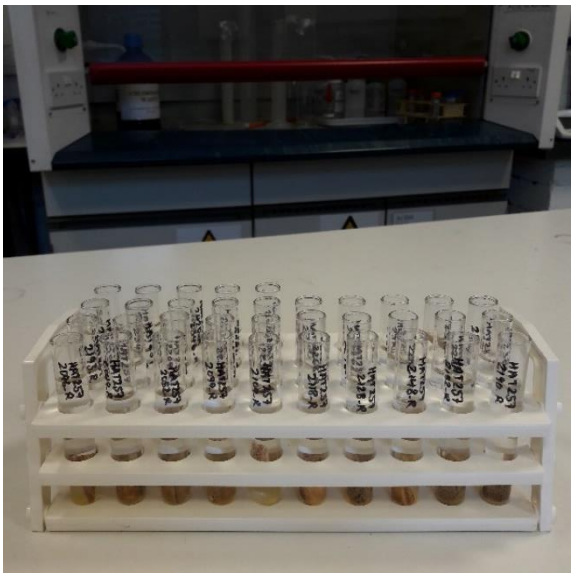


Figure 26: Bone samples demineralising in 0.5M aq. HCl

Once partially cooled, the samples were filtered using Ezee filters (60-90µm) and the supernatant liquid was poured into pre-weighed plastic transport tubes and capped with pierced parafilm (Figure 27).

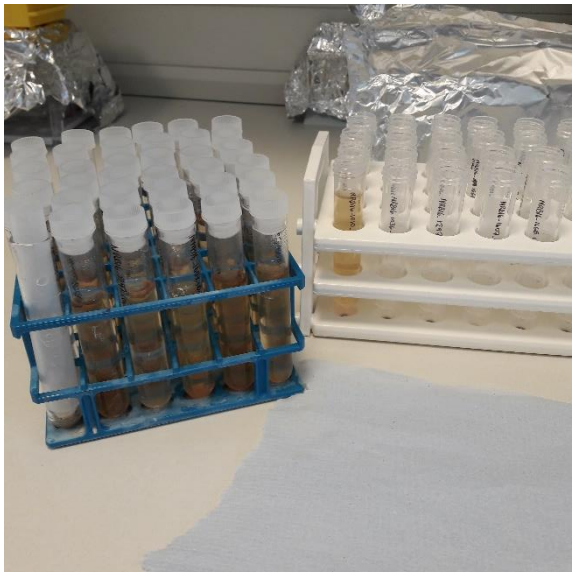


Figure 27: Ezee filtering gelatinised bone samples into plastic transport tubes

The samples were then placed into a -20°C freezer until completely frozen (c. 48hr), then transferred to a -80°C freezer for at least 4hr. Following this, the samples were placed into a freeze-drier until fully lyophilised (c. 5 days) (Figure 28).



Figure 28: Example of fully lyophilised collagen

5.3.2.3 Collagen Extraction: Aquatic Faunal Bone

The process of collagen extraction from fish bone was similar to that described above but required an extra de-fatting stage as fish bone tends to retain more fat than human or terrestrial faunal bone, which could affect isotope results.

Samples were de-fatted using a modified version of the de-fatting stage in the McDonald Institute lab protocol for collagen extraction from modern bone (Appendix VII). Samples were placed into pre-weighed glass test tubes and approximately 8ml of 2:1 methanol:chloroform (CH_3OH:$CHCl_3$) was added. The samples were then ultrasonicated for 15min, followed by 5min in the centrifuge at 2500 RPM. The solvent was then replaced, and the process was repeated until the solvent remained clear (up to 15 rinses). The process was then repeated with 2:1 chloroform:methanol. Samples were then rinsed once with distilled water and left to dry overnight, before re-weighing the test tubes. Following this de-fatting stage, the process of demineralisation and lyophilisation was the same as for human/terrestrial faunal bone.

5.3.2.4 Isotope Ratio Mass Spectrometry

All collagen samples were run in triplicate. For each analysis 0.8mg (±0.1mg) of the lyophilised collagen from each sample was weighed into a tin capsule (Figure 29). For each batch of samples submitted for analysis, a suite of in-house standards were also weighed into tin capsules and analysed (caffeine, alanine, nylon, protein, EMC). Analysis of collagen samples (and standards) was carried out using a Costech automated elemental analyser coupled in continuous -flow mode with a Thermo Finnigan MAT253 isotope ratio mass spectrometer in the Godwin Laboratory, Department of Earth Sciences, Cambridge, by Catherine Kneale. All samples are reported on the international scale relative to VPDB for carbon and AIR for nitrogen (Hoefs 1997). Based on replicate analyses of standards, analytical error was <±0.2‰.

All results were quality checked to see if they were within the acceptable atomic C:N ratio range of 2.9-3.6 (DeNiro 1985) and above the minimum acceptable %C and %N threshold (taken as >13% for C and >4-5% for N (Ambrose 1990)).



Figure 29: Example of weighed tin capsule containing collagen

5.3.3 Enamel Carbonate Carbon and Oxygen Isotope Analysis Methodology

Sampling and preparation of tooth enamel for carbonate isotope analysis was carried out in the Dorothy Garrod Laboratory, McDonald Institute, University of Cambridge, following lab protocols (Appendix VII) based on methods established by Marie Balasse (e.g. Balasse *et al.* 2002), after training from Catherine Kneale and Emma Lightfoot.

5.3.3.1 Enamel Preparation

The downflow extraction hood and drill equipment were prepared for tooth enamel sampling by wiping down with Kimtech wipes and methanol. Dental calculus adhering to the enamel surface was removed using a clean scalpel and stored in a labelled micro-centrifuge tube for potential future analysis. The outer surface of the tooth enamel was abraded using a hand-held Dremel drill with a round-headed, diamond-tipped drill bit in a downflow extraction hood to remove surface contaminants. The resulting enamel powder was disposed of. A smaller, round-headed diamond-tipped drill bit was cleaned using methanol and used to abrade the enamel using transverse movements from the crown to the EDJ of the tooth, avoiding any dentine (Figure 30). Approximately 5.5-10mg of enamel powder was collected into weighing paper and poured into a pre-weighed and labelled micro-centrifuge tube. Any unpowdered chunks of enamel in the sample were ground in a cleaned agate pestle and mortar and sieved (90μm).

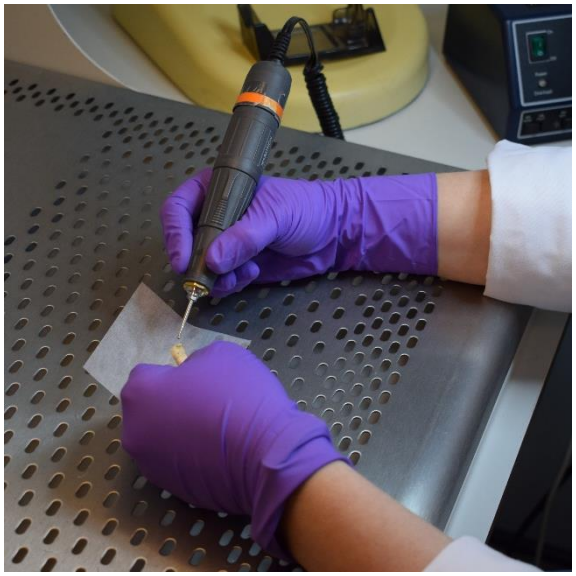


Figure 30: The author collecting enamel powder using hand-held Dremel drill

5.3.3.2 Bioapatite Extraction

Depending on the size of the centrifuge, between 18-20 samples (plus four standards) could be processed for bioapatite extraction at a time. To extract the bioapatite from the tooth enamel, approximately 0.1ml per mg of sample of 2-3% aq. sodium hypochlorite (NaOCl) was added to each micro-centrifuge tube and then all samples were vortex mixed and left for 24hr in a fridge. Samples were then placed in a centrifuge at 8000rpm for 5min and the sodium hypochlorite solution was then decanted. Distilled water was then added to each tube, followed by vortex mixing, placement into a centrifuge at 8000rpm for 5min and then decanting of the distilled water (Figure 31). This process was repeated four more times. Any liquid remaining in the tubes was removed using a micro-pipette with disposable tips. Approximately 0.1ml per mg of sample of 0.1M aq. acetic acid (CH_3COOH) was added to each micro-centrifuge tube. All samples were then vortex mixed and left at room temperature for 4hr. Distilled water was then added to each tube, followed by vortex mixing, placement into a centrifuge at 8000rpm for 5min and then decanting of the distilled water. This process was repeated four more times. Any remaining liquid was removed using a micro-pipette with disposable tips.



Figure 31: The author extracting bioapatite for carbonate isotope analysis

The micro-centrifuge tubes were then capped with pierced parafilm and frozen at -20°C (c.2hr) and then placed in a freeze drier until full lyophilisation (c.4hr) (Figure 32). The resulting powder and tube were then weighed. Four in-house enamel standards were subject to the same treatment described above, to check for methodological issues.



Figure 32: Example of fully lyophilised enamel powder sample before weighing into glass gas bench tube

5.3.3.3 Isotope Ratio Mass Spectrometry

For each sample, approximately 2-4mg of enamel powder was weighed into pre-weighed and labelled glass gas bench tubes. For each batch of samples submitted for analysis, 2-4mg of two in-house faunal enamel standards were also weighed into glass gas bench tubes (eight standard tubes in total). Samples were then transferred to the Godwin Laboratory, Department of Earth Sciences, Cambridge where James Rolfe carried out the next stages of preparation, following the Godwin Laboratory protocols. The glass vials were vacuum-sealed, and the samples were reacted with 100% orthophosphoric acid at 90°C using a Micromass Multicarb Sample Preparation System. The CO_2 produced was then dried and transferred cryogenically into a Gas Bench II coupled to a Delta V mass spectrometer for isotope analysis. All results for both carbon and oxygen are measured and reported on the international scale relative to VPDB calibrated through the NBS19 standard (Coplen 1995, Hoefs 1997). Analytical error was $<\pm 0.08‰$ for $\delta^{13}C$ and $<\pm 0.10‰$ for $\delta^{18}O$.

5.3.3.4 Conversion Equations

Enamel phosphate $\delta^{18}O$ (VSMOW) values were calculated from the enamel carbonate $\delta^{18}O$ (VPDB) values using conversion equations in Coplen (1988) ($\delta^{18}O_c$ (SMOW) = 1.03091 x $\delta^{18}O_c$ (VPDB) + 30.91), then Chenery *et al.* (2012) ($\delta^{18}O_p$ (SMOW) = 1.0322 x $\delta^{18}O_c$ (SMOW) - 9.6849). However, due to the increasing margins of error introduced through conversion equations, all analysis of $\delta^{18}O$ values discussed in this thesis use the unconverted carbonate $\delta^{18}O$ (VPDB) values.

5.3.4 Strontium Isotope Methodology

5.3.4.1 Enamel Preparation

Tooth enamel was prepared using a modified version of the National Oceanography Centre Southampton protocol (Nafplioti 2008, 2009) (Appendix VII) in the Dorothy Garrod Laboratory, McDonald Institute, University of Cambridge, after initial assistance from Argyro Nafplioti. Further sample preparation was undertaken in the Isotope Geochemistry Laboratory, Department of Earth Sciences, Cambridge, following Isotope Geochemistry protocols.

Before sample preparation, all glass beakers were cleaned by rinsing in ultrapure water (18.2Ω). Following this, they were then partially filled with ultrapure water and ultrasonicated for 5min. This process was repeated three times. They were then rinsed three times in ultrapure water and dried in an oven at 50-75°C. Drill bits were cleaned in cleaned glass beakers following the same process.

Teeth were initially cleaned to remove surface dirt and contaminants by placing them in separate clean glass beakers, immersing them in ultrapure water and placing them in an ultrasonic bath for 30min. Following this, the water in the beaker was discarded and each tooth was manually cleaned using a new toothbrush and ultrapure water, rinsing the toothbrush between each tooth. This process was repeated three times. The teeth were then rinsed three times with ultrapure water and dried in an oven at 50°C. Once dry, teeth were transferred into new, labelled, plastic zip-lock bags.

Work surfaces, extraction hoods and drill equipment were prepared for tooth enamel sampling by wiping down with Kimtech wipes and methanol (CH_3OH), followed by wiping down with ultrapure water. The drilling area was also prepped with aluminium foil wiped with ultrapure water. In a dust extraction hood, the surface of each tooth was abraded using a hand-held Dremel drill with a clean, round-headed, diamond-tipped drill bit to remove further surface contaminants (Figure 33, Figure 34). The bulk of the dentine was also drilled away (Figure 34).

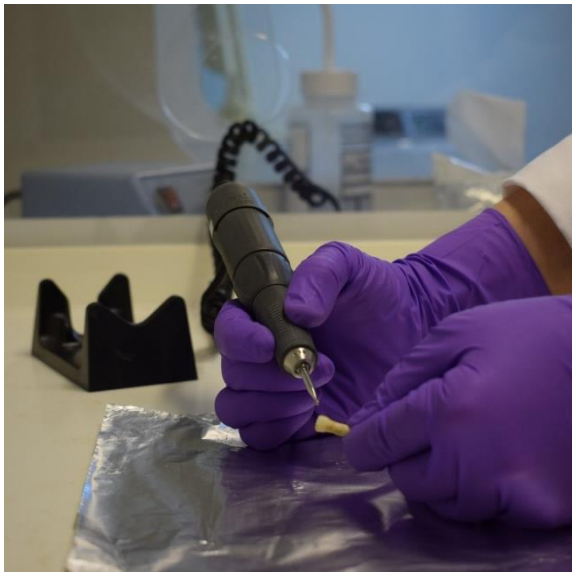
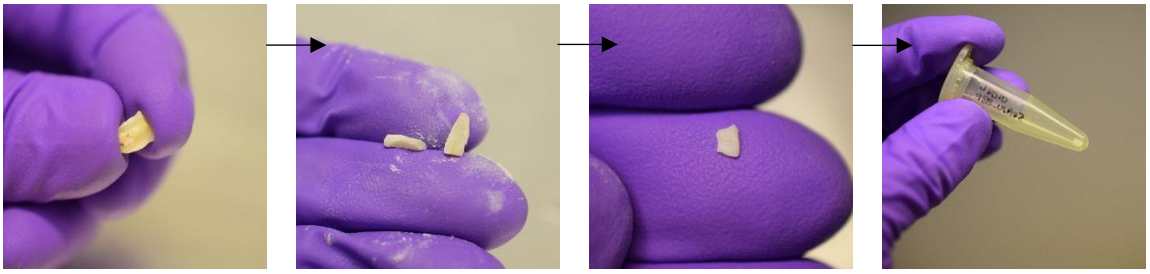


Figure 33: The author carrying out initial abrasion of the enamel surface with a hand-held Dremel drill

The tooth was then transferred to a downflow extraction hood equipped with a magnifying lamp. An enamel chip of c.20-50mg was prepared using second a hand-held Dremel drill with a clean, round-headed, diamond-tipped drill bit to drill away the rest of the dentine and further clean all exposed surfaces of the tooth enamel. The enamel sample was then placed into a new, pre-weighed, labelled micro-centrifuge tube and was re-weighed (Figure 34).



Tooth crown cut longitudinally to expose dentine; external enamel surfaces abraded

Bulk of dentine removed (in this case, the enamel broke once dentine removed)

All surfaces of remaining chip abraded

Enamel chip ready for next stage of processing for Sr isotopes

Figure 34: Step by step example of tooth enamel chip preparation for Sr isotope analysis

Further cleaning to remove potential surface contaminants, dentine powder and some diagenetic strontium was carried out following leaching steps in Nafplioti (2009) modified from Bentley (2004). Approximately 2ml of ultrapure water was added to each enamel sample in the micro-centrifuge tubes using a 200-1000µl micropipette with disposable tips. The micro-centrifuge tubes were re-closed and placed in a rack in an ultrasonic bath for 20min. The ultrapure water was then removed from each tube and each sample was rinsed four times in the tube using ultrapure water and clean pipette tips. 2ml of 5% aq. acetic acid was then added to each enamel sample in the micro-centrifuge tubes using a 200-1000µl micropipette. Samples were then left for 1hr at room temperature. Following this, the acetic acid was removed, and each sample was rinsed four times in the tube using ultrapure water and clean pipette tips. The waste acetic acid and ultrapure water (leachates) was retained in new, plastic transport tubes. A further 2ml of 5% aq. acetic acid was added to each tube, which were then re-closed and left overnight (c.12-15hr) at room temperature. The samples were rinsed a further four times in the tube using ultrapure water and clean pipette tips. Again, the waste acetic acid and ultrapure water (leachates) was retained in new, plastic transport tubes. The micro-centrifuge tubes were then placed in a heatproof rack in an oven at 60°C until dry (c.3-5hr). The lids were left open with a sheet of aluminium foil covering the rack to prevent air-borne debris settling in the open tubes. Once dry, samples were removed from the oven, lids were reclosed and micro-centrifuge tubes were placed in a new, labelled plastic zip-lock bag for transferal to the Department of Earth Sciences, Cambridge.

5.3.4.2 Preparation of Samples for Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) and Thermal Ionisation Mass Spectrometry (TIMS)

Enamel samples were prepared for analysis with ICP-OES and TIMS following the Isotope Geochemistry Laboratory protocol by Nick Evans (Appendix VII) in a class 100 laminar flow clean cabinet in the class 10000 Isotope Geochemistry Laboratory, Department of Earth Sciences, University of Cambridge, under the supervision of Harold Bradbury.

All work in the Isotope Geochemistry Laboratory was carried out in acid-cleaned Savillex Teflon beakers. Teflon beakers were cleaned in the Isotope Geochemistry Laboratory over five days following a protocol by Harold Bradbury, Department of Earth Sciences (Appendix VII)

using a process of rinsing three times in MilliQ ultrapure water, heating overnight on a hotplate in 50% aq. nitric acid (HNO_3), rinsing three times in MilliQ ultrapure water, heating overnight on a hotplate in 50% aq. hydrochloric acid (HCl), rinsing three times in MilliQ ultrapure water, heating overnight on a hotplate in MilliQ ultrapure water with a dash of concentrated nitric acid, rinsing three times in MilliQ ultrapure water and then leaving to dry.

Leached enamel samples were tipped from the micro-centrifuge tubes into acid-clean, labelled Teflon beakers. 1ml of 6M aq. nitric acid was added to each beaker, the lids were re-secured and the samples were digested on a hotplate at 90°C for approximately 2hr. Once the enamel was fully dissolved, 3ml of MilliQ ultrapure water was added to each beaker to make a solution of 4ml.

5.3.4.3 Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES)

To obtain element concentration data, samples were subsampled for analysis with ICP-OES in a fume hood the ICP-OES Laboratory, Department of Earth Sciences, University of Cambridge. A variable amount of each solution (capped at 25µl) was taken from the Teflon beakers using a 2-20µl micropipette and a clean pipette tip and transferred to a new, micro-centrifuge tube. The amount of each solution required in µl was calculated using the weight of the sample post-leaching following the formula ROUND((100/((sample weight (mg)* 0.398406374501992)*)*1000),0). This solution was then made up to 500µl with 0.1M aq. nitric acid using a 20-200µl micropipette. The lid of each of the micro-centrifuge tubes was cut off and the samples were introduced into the ICP-OES. All samples were run on an Agilent 5100 ICP-OES in the Department of Earth Sciences, Cambridge, with the supervision of Harold Bradbury and Mervyn Greaves. Samples were run with a large set of internal standards of varying known Sr concentrations.

5.3.4.4 Strontium Isolation by Column Chemistry

Column chemistry was carried out to isolate the strontium in the digested enamel samples following the Isotope Geochemistry Laboratory protocol by Nick Evans (Appendix VII). The protocol was carried out in a class 100 laminar flow clean cabinet in the class 10000 Isotope

Geochemistry Laboratory, Department of Earth Sciences, University of Cambridge, after training from Harold Bradbury and Alena Giesche.

Due to the number of columns available and complex timings involved, only four samples at a time could be processed for strontium isolation. Before starting the columns, a batch of 200µl and 1000µl pipette tips were cleaned by taking up and discarding 8M aq. nitric acid three times, then repeating three times with MilliQ ultrapure water. A variable amount of each sample (based on calculations from the concentrations generated by the ICP-OES) was pipetted into acid-clean, labelled Teflon beakers, using a 200-1000µl micropipette and clean tips. The beaker lids were removed, and beakers placed onto a hotplate at 90°C overnight to dry down. Once dry, the sample was re-dissolved in 200µl of 3M aq. nitric acid and placed back on hotplate at 90°C for 1hr with the lid on to reflux. Four pre-prepared columns were set up in a manifold, with 'waste' Teflon beakers placed underneath (Figure 35). Columns were filled with 8M aq. nitric acid using a 200-1000µl micropipette. This was repeated once all nitric acid had passed through. Columns were then filled with MilliQ ultrapure water. This was repeated once all water had passed through. ~120µl of Sr spec resin was added to each column using an adjustable 20-200µl micropipette. Columns were then again filled to the top with MilliQ ultrapure water. This was repeated once all water had passed through. 200µl of 3M aq. nitric acid was then passed through each column 3 times using an adjustable 20-200µl micropipette. The samples were then removed from the hotplate and added to the columns using a 200-1000µl micropipette and clean pipette tips. 100µl of 3M aq. nitric acid was then passed through each column five times. The beakers below the columns were then switched for acid-clean, labelled Teflon beakers and 200µl of MilliQ ultrapure water was passed through the columns, followed by 100µl of MilliQ ultrapure water, four times (600µl in total), flushing out the strontium into the beakers. Once the sample had been collected, the columns were cleaned with MilliQ ultrapure water and two rinses with 8M aq. nitric acid.

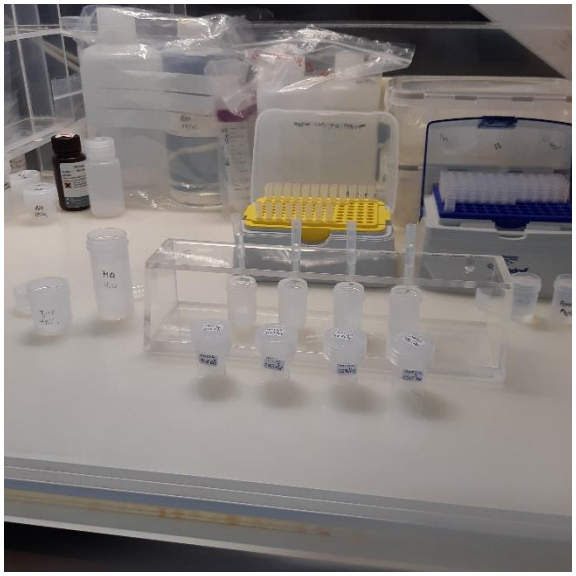


Figure 35: Four strontium columns set up in manifold

5.3.4.5 Preparation of Filament Plates for Thermal Ionisation Mass Spectrometry (TIMS)

Before TIMS analysis, filament plates, coverslip plates and backplates for the TIMS turret (Figure 37) had to be cleaned and prepared to avoid cross-contamination. Any remaining rhenium (Re) filaments were removed from the posts on used filament plates by abrasion using a Dremel drill with a flat diamond-tipped drill bit (Figure 36). Abrasive aluminium powder was mixed with dilute aq. nitric acid to form an abrasive paste and applied to the filament plates, coverslip plates and back plates using clean cotton buds. The plates were then placed into labelled plastic zip-lock bags and transferred to the TIMS Laboratory, Department of Earth Sciences, University of Cambridge.

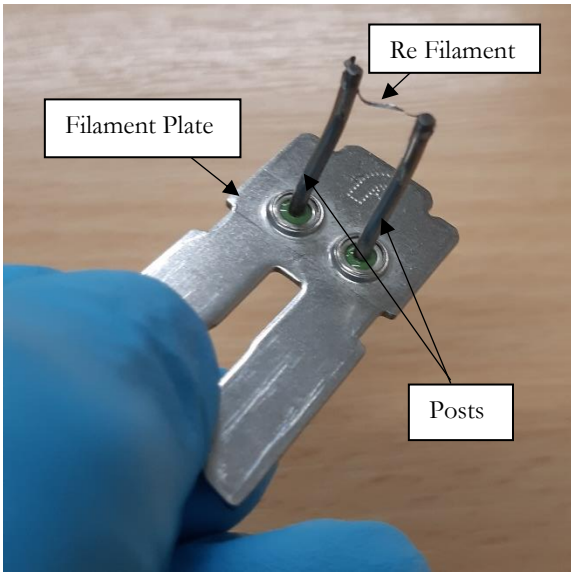


Figure 36: Elements of filament plate used in TIMS turret

The turret filament plates, coverslip plates and back plates were then washed and dried in the TIMS laboratory. A large glass beaker was rinsed three times in MilliQ ultrapure water. The plates were placed into the beaker and rinsed with MilliQ ultrapure water three times, then covered with MilliQ ultrapure water and placed in an ultrasonic bath for 20min, stopping after 10min to pour away and replace the water. The plates were rinsed three more times with MilliQ ultrapure water and then placed in an oven at 100-120°C for c.12-24 hours to dry.

New Re filaments were attached to clean filament plates by placing the filament plate into a specially designed clamp. A c.2cm strip of 0.7mm Re ribbon was also placed into the clamp and the clamp was turned until the Re strip touched each post on the filament plate. A spot welder was used to weld each end of the Re strip to the posts. Fifteen completed filament plates at a time were then loaded into an outgasser and outgassed for 73min.

5.3.4.6 Thermal Ionisation Mass Spectrometry (TIMS)

Samples were dried down to isolate the strontium for analysis with TIMS following the Isotope Geochemistry protocol by Nick Evans (Appendix VII) in the class 10000 Isotope Geochemistry Laboratory, Department of Earth Sciences, University of Cambridge, following training by Harold Bradbury.

Due to the capacity of the TIMS turret, samples were prepared in batches of 16, allowing space for five standards per turret. Sixteen samples collected from the column chemistry step were placed on a hotplate at 90-100°C for at least 3-4 hours with the lids removed until the samples had dried down to a tiny, solid 'dot' in the beaker. The lids were put back on and samples were placed in a rack inside a clean, plastic zip-lock bag and transferred to the TIMS Laboratory, Department of Earth Sciences.

All samples were loaded onto filament plates in a fume hood in the TIMS Laboratory, Department of Earth Sciences, Cambridge, following training by Harold Bradbury. Due to the capacity of the filament 'sample loading' equipment, only five filament plates could be loaded at a time. To prepare the five Sr standards, five pre-prepared outgassed filament plates were placed onto the sample loader. A 0.8A current was passed through all of the filaments and a strip of parafilm was used to coat each end of the Re strip, leaving a c.3mm area free in the centre of the strip. 0.5µl of tantalum (Ta) activator was dropped in the centre of each Re strip using a 0.5-10µl micropipette and a pipette tip rinsed twice with 1µl of 8M nitric acid. Once this had dried down (c.<1min), a micropipette tip was rinsed out twice with 1.5µl 8M aq. nitric acid, then twice with 1.5µl 2M aq. nitric acid. 1µl of a Sr standard (NBS 987) was pipetted in the centre of the each Re strip and allowed to dry down (c.<1min). The current was then slowly increased over c.30sec to c.1.8A to burn off the remaining parafilm, then was increased to c. 2.0A until all Re filaments glowed red, burning off any other potential contaminants. The filament plates were then removed from the sample loader and stored in covered plastic holders while the next five pre-prepared outgassed filament plates were placed in the sample loader. For the 16 samples, the Re strips were prepared with parafilm and Ta activator as before. A micropipette tip was rinsed twice with 1.5µl of 8M aq. nitric acid, then twice with 1.5µl 2M aq. nitric acid, then 1.0µl 2M aq. nitric acid was taken up in the micropipette and deposited onto a dried Sr sample in a Teflon beaker to re-dissolve it to be transferred to the filament. The sample was then pipetted onto the centre of the first Re strip and allowed to dry down (c.<1min). This process was repeated with clean pipette tips for the next four samples, followed by the burning stage. This whole process was then repeated until 16 samples and five standards were prepared for the TIMS turret.

The filament plates, backplates and coverslips were then inserted into the TIMS turret before being placed into a ThermoScientific Triton+ TIMS (Figure 37). The TIMS analysis was supervised by Harold Bradbury during each run. Each sample was typically heated and the ratio analysed >100 times before burning out. The average ratio for each sample was calculated from these repeats, with a mean SD of 0.000013 for all the samples (including two samples with high SDs of 0.000429 and 0.000320). The mean SD of all of the replications of the NBS 987 standard was 0.000017, although this includes one erroneous result, with an SD of 0.000616. The mean SD over all of the replications of the standard, excluding this, was 0.000006.

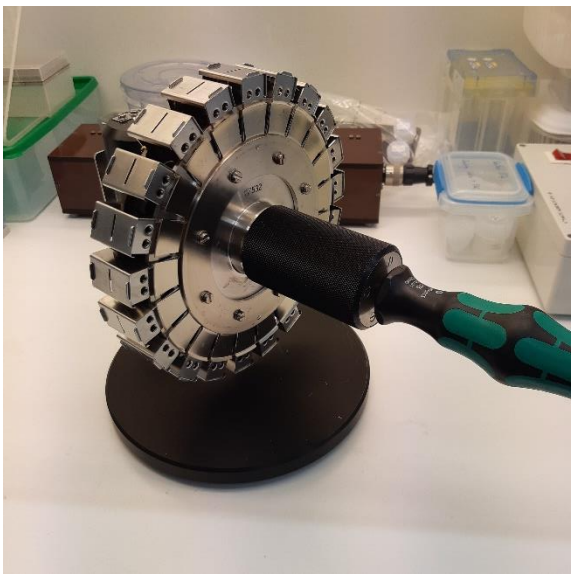


Figure 37: Fully loaded turret ready for TIMS analysis

5.4 Data

5.4.1 Data Recording

A physical paper lab book was kept throughout all laboratory procedures, containing lists of samples taken, weights, protocol notes etc. After submission of this thesis, the lab book will be kept in the McDonald Institute, University of Cambridge and should be available for future reference. All lists of samples taken, as well as the relevant weights, were also copied up into 'Master' Microsoft Excel spreadsheets for carbon and nitrogen, carbon and oxygen and strontium analyses.

All raw isotope data from various laboratory analyses was reported in Excel spreadsheets. A copy of all raw data received was kept exactly as was reported. Once the raw data was checked for quality, the data was also copied into the 'Master' Excel spreadsheets. This isotope data was also routinely sent to Sarah Inskip of the 'After the Plague' project throughout the PhD so that it could be integrated with the project Microsoft Access database. Once all the data was collected, a final copy of the isotope data was deposited in the project Microsoft Access database.

5.4.2 Data Exploration and Statistical Analysis

All statistical analysis and graphical representations were produced in R version 4.0.2, using R Studio version 1.3.959.

For most analyses, the δ isotope values were used. In cases where further exploration required a calculation *between* δ values, such as calculating the difference between rib and dentine $\delta^{15}N$ values, then one value was subtracted from the other, creating Δ isotope values.

An emphasis on data exploration and visual representations of data, beyond the standard $\delta^{13}C$/ $\delta^{15}N$ scatterplot, was employed. Boxplots (Tukey 1977), violinplots (Hintze and Nelson 1998), raincloud plots (Allen *et al.* 2019) and bagplots (Rousseeuw *et al.* 1999) were found to be effective ways of representing isotope data, which allowed for visual examination of the range and shape of the data spread, and observations of outliers. Most plots were produced using packages within Tidyverse, primarily 'ggplot2'.

Raincloud plots were produced following Allen *et al.* (2019), using code by Allen *et al.*, and the package 'cowplot'. Raincloud plots combine a 'split-half violin' plot (showing the probability density), a boxplot (showing the median and interquartile range (IQR)) and a jittered raw data scatterplot. This allows for comprehensive visualisation of data, although only one isotope can be effectively visualised at a time.

Bagplots were produced using following Rousseeuw *et al.* (1999) using R code produced by Ben Marwick (2016). Bagplots display data in a similar way to boxplots but in two dimensions, showing the depth median, range and outliers, allowing for the visualisation of the 'location, spread, correlation, skewness and tails of the data' (Rousseeuw *et al.* 1999, p. 382). Bagplots are constructed using the principle of halfspace location depth (Tukey 1975). The 'plus signs' represent the depth median of each group, inner rings, or 'bags' contain 50% of all of the points around the depth median, and outer rings, or 'loops' contain all points within a region calculated by inflating the inner bag by a factor of three, relative to the depth median. The loop is analogous to the 'whiskers' of a boxplot and any data points outside of the loop are considered to be outliers. Performing this type of bivariate analysis on variables that are not independent (i.e. $\delta^{13}C$ and $\delta^{15}N$ in collagen) can result in differences in identified outliers than when each variable is considered using univariate methods (Bertani *et al.* 2018). As bagplots are a bivariate method, two isotopes to be visualised at the same time, mirroring more the more familiar scatterplot format.

Statistical analysis was primarily undertaken using package rstatix, following Kassambara (2019). Where *p*-value based null hypothesis testing was used, appropriate testing of assumptions was carried out to make sure there were no major violations of the methods (as far as is possible with archaeological data), and non-parametric testing was applied where appropriate. Any *p*-values generated were included in context and making conclusions drawn primarily from *p*-values alone was avoided.

For more complex analysis, *DetectDeviatingCells* (DDC) (Rousseeuw and Bossche 2018) was found to be an effective way to visually inspect and interrogate the large multivariate isotope dataset for outliers. The method works by inputting multiple numeric-only variables as columns, with the dependent variable as rows. In this case, the dependent variable was each skeleton, represented by a PSN, and the columns were the numeric results of various analyses, e.g. $\delta^{13}C$

values. DDC then standardises the data by column and detects columnar outliers. It then calculates predicted values for all cells in each row (i.e. for each skeleton), based on data from the columns but importantly, it factors correlations between columns into the predictions, so the method works better the more (suitable) columns are included. The method then flags cells whose 'true' value deviates from the predicted value – red indicates the value is higher than predicted, blue indicates it is lower than predicted. While this method is somewhat limited for isotope data, as most isotope values tend to be independent variables, it never-the-less provides a powerful visual aid, not only to detect biological outliers, but also to detect potential sample contamination or even potential typographical errors. Analysis was carried out using the default DDCpars parameters, where a cell is flagged as outlying if the standardised value is greater than the cut off of 2.576, corresponding to a tolerance of 99%.

In combination, these methods allowed for comparisons of data on a population and individual scale and allowed for analysis of differences between groups of interest.



6. Data Quality and Character

This chapter summarises the overall success, quality, distribution and character of the whole faunal and human isotope dataset before the data is explored in more detail in Chapters 7 and 8. Full faunal and human isotope results can be found in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053), and summary statistics can be found in Appendix I. Where further statistical tests are used, corresponding full statistical analysis can be found in Appendix VI.

6.1 Sample Success and Data Quality

This section summarises the overall success of the isotope analysis, indicating how many samples were taken, how many produced good quality data and how many were rejected due to poor data.

6.1.1 Faunal Bone Collagen Carbon and Nitrogen Isotope Analysis

246 faunal bones (including fish) from six Cambridgeshire sites were analysed for bone collagen $\delta^{13}C$ and $\delta^{15}N$ as part of this thesis. Of these, only eight failed to produce data. These were of various species from five different sites, indicating the failures were not due to poor preservation at one particular site. All successful samples had %C and %N above the minimum acceptable threshold (taken as for >13% C and >4-5% for N (Ambrose 1990)). Only two of the **238** successful samples yielded collagen with an atomic C:N ratio outside of the acceptable range (taken as 2.9-3.6 for bone (DeNiro 1985)). In these cases (SJT07_1666_BOV_a & NRB16_2088_PIG_a), the aliquots with unacceptable results were excluded, resulting in $\delta^{13}C$ and $\delta^{15}N$ values being calculated from duplicate rather than triplicate aliquots. There were also

nine samples where one of the aliquots completely failed and could not be repeated, meaning these $\delta^{13}C$ and $\delta^{15}N$ values were calculated from duplicate aliquots only.

In addition to the **238** faunal bones which produced successful results as part of this thesis, $\delta^{13}C$ and $\delta^{15}N$ results from nine cod from Cambridge Grand Arcade, three cod from Hostel Yard Corpus Christi and four cod from St John's Triangle (Barrett *et al.* 2011) have been incorporated into the primary dataset for Cambridgeshire, totalling **254** faunal bones with $\delta^{13}C$ and $\delta^{15}N$ results.

On initial review of the results, it was clear that the $\delta^{13}C$ and $\delta^{15}N$ results for the cyprinid fish bone collagen were extremely wide-ranging. The $\delta^{13}C$ values had a range of 11.3‰, from -11.6 to -22.9‰ and the $\delta^{15}N$ values had a range of 10.6‰, from 10.7‰ to 21.3‰. Comparable isotope analysis of cyprinid bone from Anglian and Medieval contexts from Yorkshire showed much smaller ranges ($\delta^{13}C$= 5.1‰, $\delta^{15}N$=3.3‰, n=4) (Müldner and Richards 2005, 2007b). Although freshwater fish are known to have high variation in isotope values (e.g. Dufour *et al.* 1999, Fuller *et al.* 2012, Häberle *et al.* 2016), the large range in the Cambridgeshire samples seems suspect, particularly for sample EGN12_1336_CYP, whose $\delta^{13}C$ value of -11.6‰ places it closer to values for marine, rather than freshwater fish, and sample EGN12_1612_CYP, whose $\delta^{15}N$ value of 21.3‰ places it well above even pike in terms of trophic level. I decided to exclude these two samples, reducing the final number of faunal bone $\delta^{13}C$ and $\delta^{15}N$ results to **252**.

6.1.2 Human Dentine and Bone Collagen Carbon and Nitrogen Isotope Analysis

227 human tooth roots from eight Cambridgeshire sites were analysed for tooth dentine collagen $\delta^{13}C$ and $\delta^{15}N$ and **314** human ribs from 11 Cambridgeshire sites were analysed for bone collagen $\delta^{13}C$ and $\delta^{15}N$ as part of this thesis. Of these, only four rib samples failed to produce any data. These were all from Vicar's Farm and were probably a consequence of the very poor bone preservation at the site. All successful dentine and rib samples had %C and %N above the minimum acceptable threshold. Three out of the **227** successful dentine samples and two out of the **310** successful rib samples had one aliquot with an atomic C:N ratio outside of the acceptable range and/or unacceptably large standard deviation between the aliquot

triplicates. For these, (HAT257_2306_LRPM2_D, HAT257_2279_URM2_D, HAT257_2323_LLPM2_D, JDS10_1400_R & HAT257_2382_R), the results of the outlying triplicate were excluded, resulting in $\delta^{13}C$ and $\delta^{15}N$ values calculated from duplicate rather than triplicate aliquots. For three rib samples (JDS10_1292_R, JDS10_5153_R & HAT358.1_4252_R) one of the three aliquots failed and could not be repeated, also resulting in $\delta^{13}C$ and $\delta^{15}N$ (‰) values calculated from duplicate rather than triplicate aliquots.

In addition to the **310** ribs which produced successful results as part of this thesis, $\delta^{13}C$ and $\delta^{15}N$ results from 101 human ribs from St John's Hospital (Price 2013), 26 human ribs from The Babraham Institute (Friedman 2007), 32 human ribs from Melbourn Water Lane (Hannah *et al.* 2018) and 15 ribs from Westfield Farm, Ely (Lucy *et al.* 2009) have been incorporated into the primary data set for Cambridgeshire, totalling **484** human rib bones with $\delta^{13}C$ and $\delta^{15}N$ results.

6.1.3 Human Enamel Carbonate Carbon and Oxygen Isotope Analysis

295 tooth enamel samples from 11 Cambridgeshire sites were analysed for enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ as part of this thesis. While there are no equivalent easily applicable quality checks for carbonate $\delta^{18}O$ and $\delta^{13}C$ data as there are for collagen $\delta^{13}C$ and $\delta^{15}N$ data, no analytical anomalies were reported, and the analytical error was within an acceptably small range, indicating the results from these samples are generally reliable. In addition, enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ results from **24** human teeth from The Babraham Institute (Friedman 2007) and **13** teeth from Westfield Farm, Ely (Lucy *et al.* 2009) have been incorporated into the primary data set for Cambridgeshire, totalling **332** human teeth with enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ results.

6.1.4 Human Enamel Strontium Isotope Analysis

In total, tooth enamel samples from **170** individuals from eight Cambridgeshire sites were analysed for $^{87}Sr/^{86}Sr$. For various reasons, from poor quality enamel at the initial stages, to lack of detection by the TIMS in the final analysis, there was a high rate of failure throughout the methodology. Where possible, analysis of failed samples was repeated but in total, only **131/170** tooth enamel samples produced reliable data (c.77% success rate). Notes on sample failures and repetition can be seen in the full dataset, available on Apollo.

The concentration of elemental strontium present ranged from 55.5 to 257.5 ppm with a mean of 125.0 ppm. When plotted against the $^{87}Sr/^{86}Sr$ values and compared to concentrations from all British archaeological burials presented in Evans *et al.* (2012), the data seems to follow a similar pattern, with the IQR of the strontium ppm for the Cambridgeshire individuals falling within the densest cluster of points for Britain (Figure 38).

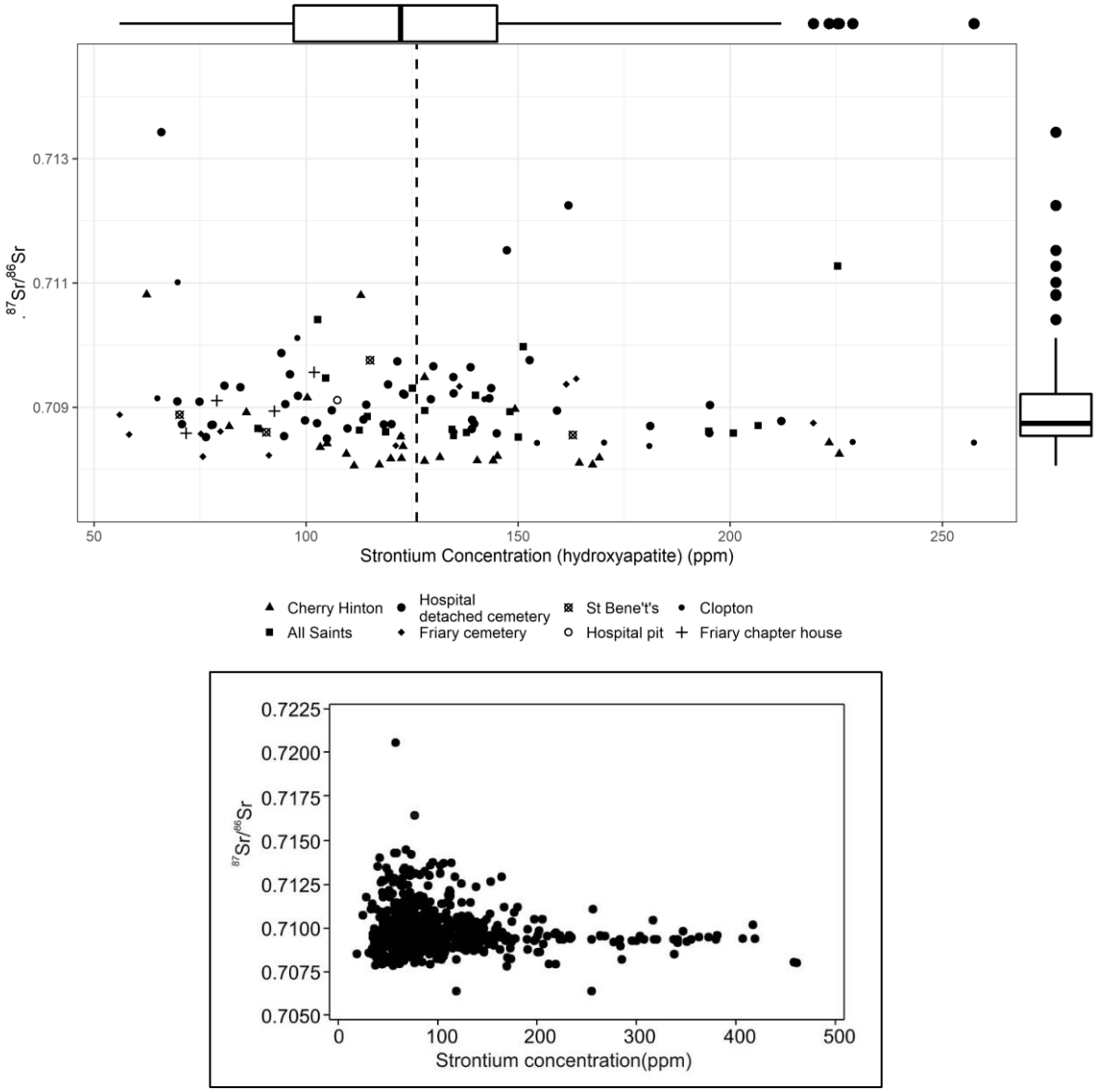


Figure 38: Tooth enamel $^{87}Sr/^{86}Sr$ values and Sr ppm concentration

Top: scatterplot, with marginal boxplots, showing tooth enamel $^{87}Sr/^{86}Sr$ values and strontium ppm concentration (calculated for hydroxyapatite), by site subgroup. Dashed black line indicates the mean strontium ppm value for all the individuals represented in the plot. Bottom: comparative plot of strontium concentration (ppm) and $^{87}Sr/^{86}Sr$ values for all British Burials (Evans et al. 2012)

6.1.5 Total Successful Isotope Results

In total, there are **252** faunal bone samples with successful $\delta^{13}C$ and $\delta^{15}N$ results in this thesis (Table 12). These are from 12 different taxa: five terrestrial fauna, two freshwater fish, four marine fish and one diadromous fish and span from the Iron Age to the Post-Medieval period.

Site	***British Archaeological/ Cultural Period***	***n***	***Fauna with Bone Collagen $\delta^{13}C$ & $\delta^{15}N$ Results***											
			Chicken/Domestic Fowl	*Cow*	*Horse*	*Pig*	*Sheep/Goat*	*Cod*	*Cyprinid*	*Eel*	*Flatfish*	*Herring*	*Ling*	*Pike*
Vicar's Farm	Iron Age	**4**		1	1		2							
	Roman	**28**	3	9		7	9							
Northstowe	Early Saxon	**19**	5	4		5	5							
	Middle Saxon	**19**	2	6		6	5							
St John's Triangle	Late Saxon	**20**	5	5		5	5							
	Late Medieval	**43**	10	10		10	10	3						
	Post-Medieval	**21**	5	5		5	5	1						
New Museums Site	High Medieval	**16**	1	5		5	5							
	Late Medieval	**39**	9	10		10	10							
	Post-Medieval	**12**	3	3		3	3							
Eastern Gate Hotel	Late Medieval	**16**						5	2	2	1	4	1	1
Grand Arcade	Late Medieval	**9**						9						
Hostel Yard Corpus Christi	Late Medieval	**3**						3						
Corpus Christi	Late Medieval	**2**						1			1			
	Post-Medieval	**1**									1			
TOTAL		**252**	**43**	**58**	**1**	**56**	**59**	**22**	**2**	**2**	**3**	**4**	**1**	**1**

Table 12: Total number of faunal samples with successful isotope results

6. Data Quality and Character

In total, there are **1174** samples from human tissues with successful isotope results in this thesis, spanning from the Neolithic to the Post-Medieval period (Table 13). **86** individuals produced successful results for dentine and rib $\delta^{13}C$ and $\delta^{15}N$ AND enamel carbonate $\delta^{18}O$ and $\delta^{13}C$ AND enamel $^{87}Sr/^{86}Sr$. This was primarily determined by the number of successful $^{87}Sr/^{86}Sr$ results.

Site Subgroup	***British Archaeological / Cultural Period***	**$\delta^{13}C$ & $\delta^{15}N$**		**$\delta^{13}C$ & $\delta^{18}O$ Enamel Carbonate**	**$^{87}Sr/^{86}Sr$ Enamel**	***Number with results for all isotope analyses***
		Dentine Collagen	***Rib Collagen***			
Trumpington	Neolithic		3			
Duxford isolated	Iron Age		1	1		
Babraham conquest	Roman		1	1		
Duxford cemetery	Roman		21	16		
Babraham	Roman		25	23		
Vicar's Farm	Roman		13	15		
Edix Hill	Early Anglo-Saxon		44	39	2	
Westfield Farm	Middle Anglo-Saxon	38	15	13		
Gamlingay dispersed	Middle Anglo-Saxon	1		1		
Gamlingay cemetery	Late Anglo-Saxon	26	35	25	6	*6*
Cherry Hinton	High Medieval	40	47	40	26	*26*
All Saints	High Medieval	31	43	34	19	*6*
Hospital detached cemetery	Late Medieval	55	149	84	46	*34*
Friary cemetery	Late Medieval	16	23	17	12	*9*
St Bene't's	Late Medieval	4		4	4	
Hospital pit	Late Medieval	1	4	1	1	*1*
Clopton	Late Medieval	12	13	12	11	*1*
Friary chapter house	Late Medieval	4	5	4	4	*3*
Holy Trinity coffins	Post-Medieval		3	1		
Holy Trinity vaults	Post-Medieval		7	3		
TOTAL		**227**	**484**	**332**	**131**	***86***

Table 13: Total number of human samples with successful results for each isotope, and total number of individuals with results for all isotope analyses

6.2 Data Distribution/Normality

This section assesses the distribution, normality and skewness of the isotope data. This is important for further interpretations and analysis, particularly relating to statistical testing.

The distribution of the faunal data shows that there is some deviation from a normal 'Gaussian' distribution in some species, particularly for pig bone collagen $\delta^{15}N$ values which appear to be weakly bimodal (Figure 39, Figure 40, Appendix VI).

The distribution of all the human data combined shows that there is some deviation from a normal 'Gaussian' distribution and that the rib collagen $\delta^{15}N$ values form a weakly bimodal distribution (Figure 41 to Figure 46). Further investigation (see Appendix VI) indicates that the distribution of the $\delta^{13}C$ and $\delta^{15}N$ values for all adult human rib collagen is not normal (Shapiro-Wilk test: $\delta^{13}C$ & $\delta^{15}N$: p=<0.001, both with positive skew). The distributions of enamel carbonate $\delta^{13}C$ and enamel $^{87}Sr/^{86}Sr$ values are also not normal (Shapiro-Wilk test: $\delta^{13}C$: p=<0.001, negative skew; $^{87}Sr/^{86}Sr$: p=<0.001, very positive skew). Overall dentine collagen $\delta^{13}C$ and $\delta^{15}N$ and enamel carbonate $\delta^{18}O$ distributions are normal (Shapiro-Wilk test: $\delta^{13}C$: p=0.08; $\delta^{15}N$: p=0.24; $\delta^{18}O$: p=0.66, positive skew).

The High/Late Medieval human dentine and rib $\delta^{13}C$ data deviates further from a normal 'Gaussian' distribution than the overall data (Figure 42), but the bimodal distribution seen in the overall rib $\delta^{15}N$ values (Figure 41) is not present, indicating that there may be changes in $\delta^{15}N$ values between the data from earlier sites compared to the High/Late Medieval sites. Further investigation (see Appendix VI) indicates that the distribution of the dentine, rib and enamel carbonate $\delta^{13}C$ values is not normal (Shapiro-Wilk test: dentine $\delta^{13}C$: p=0.008, positive skew; rib $\delta^{13}C$: p=<0.001, positive skew; enamel carbonate $\delta^{13}C$: p=<0.001, negative skew), while all $\delta^{15}N$ values follow a normal distribution (Shapiro-Wilk test: dentine $\delta^{15}N$: p=0.61, positive skew; rib $\delta^{15}N$: p=0.60, negative skew). The $\delta^{18}O$ data appears to follow a generally 'Gaussian' shape but is slightly negatively skewed (Figure 44). The $^{87}Sr/^{86}Sr$ data is not normally distributed and has a strong positive skew (Figure 46). However, further analysis (see Appendix VI) indicates that despite appearances, the distribution of the enamel carbonate $\delta^{18}O$ values is normal, but the enamel $^{87}Sr/^{86}Sr$ values are not normally distributed (Shapiro-Wilk test: enamel carbonate $\delta^{18}O$: p=0.5032, negative skew; enamel $^{87}Sr/^{86}Sr$: p=<0.0001, very positive skew).

To have some deviation from a normal distribution in a dataset that is collated from a wide variety of archaeological sites spanning over 1500+ years is to be expected and should not pose major problems for further analysis, as long as normality is checked and accounted for in further statistical testing. Given the underlying biological and geological principles of each of the isotope ratios analysed, it was not necessarily assumed that the data would follow a normal distribution. This is particularly true for $^{87}Sr/^{86}Sr$ values, where the underlying distribution of the potential variation in isotope values is not normally distributed. It is interesting that enamel carbonate $\delta^{13}C$ values have a negatively skewed distribution, with a long 'tail' towards lower values.. Overall, the distributions of the values for the High/Late Medieval period are largely as expected for each of the isotopes and re-enforces that most statistical methods employed for $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values will not be appropriate for $^{87}Sr/^{86}Sr$ data.

ALL Terrestrial Faunal Bone Collagen $\delta^{13}C$ and $\delta^{15}N$

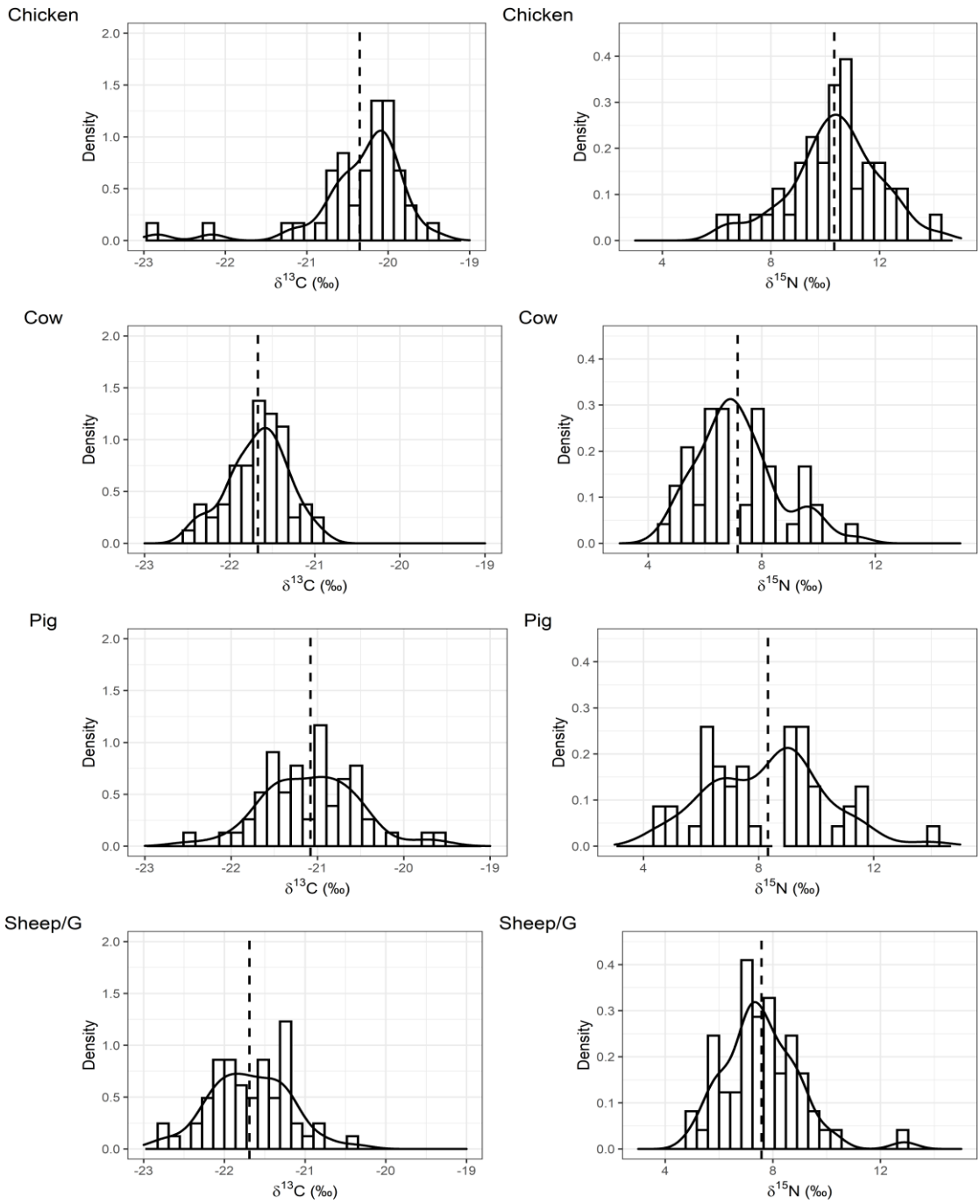


Figure 39: Histograms (with probability density) showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for all Cambridgeshire fauna analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot

High/Late Medieval Terrestrial Faunal Bone Collagen $\delta^{13}C$ and $\delta^{15}N$

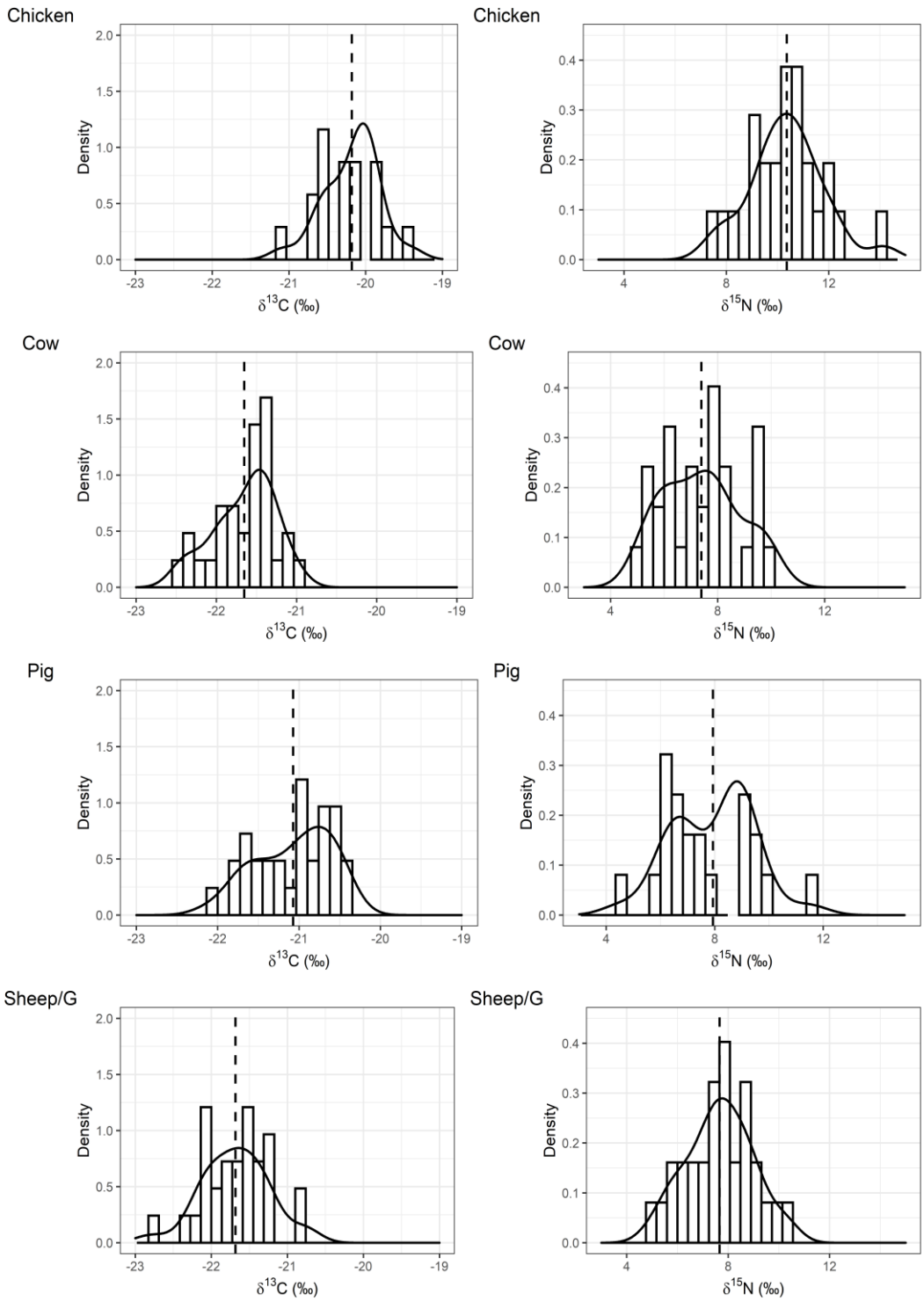


Figure 40: Histograms (with probability density) showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire fauna analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot

ALL Human Dentine and Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

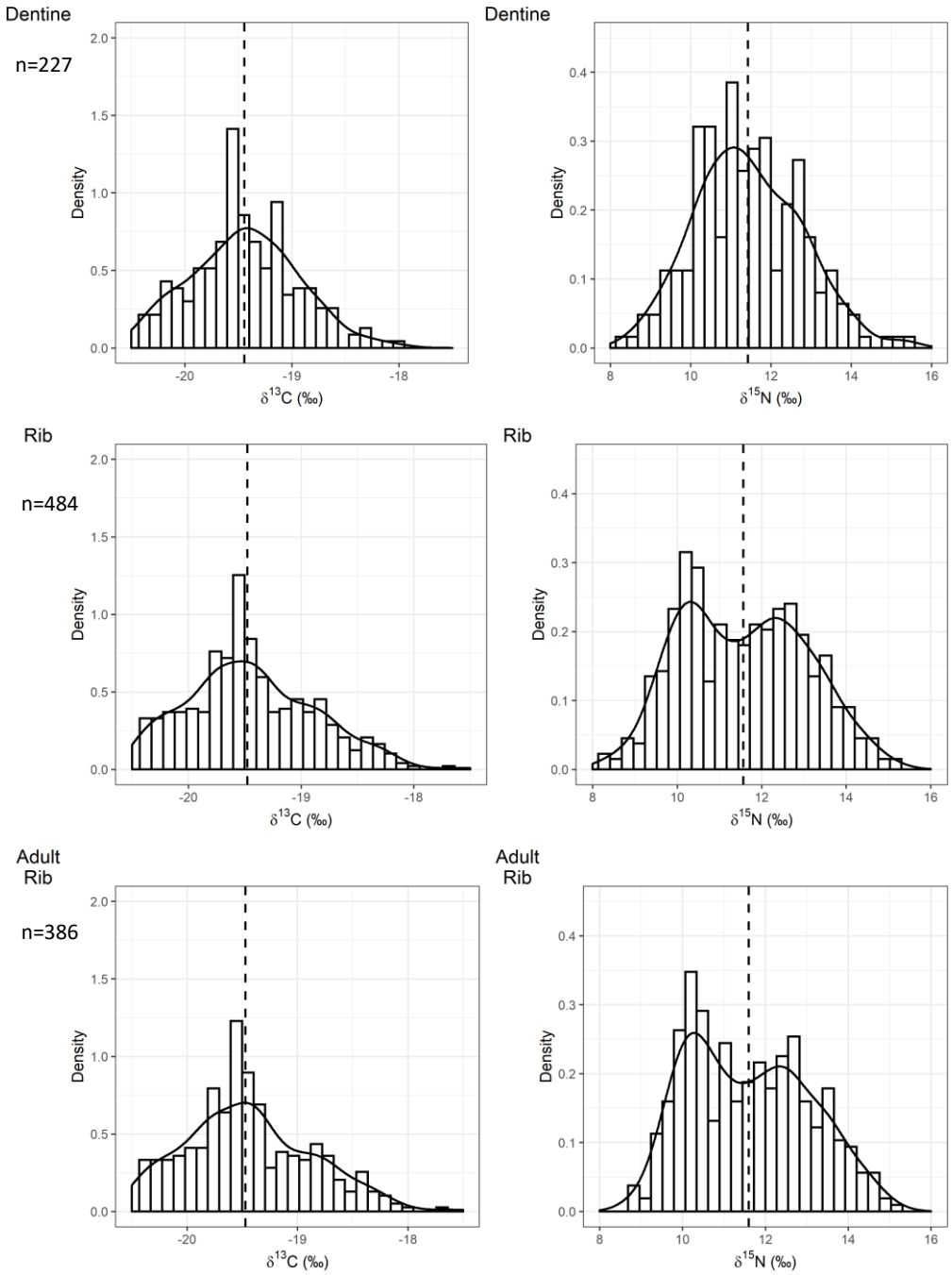


Figure 41: Histograms (with probability density) showing dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot

High/Late Medieval Human Dentine and Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

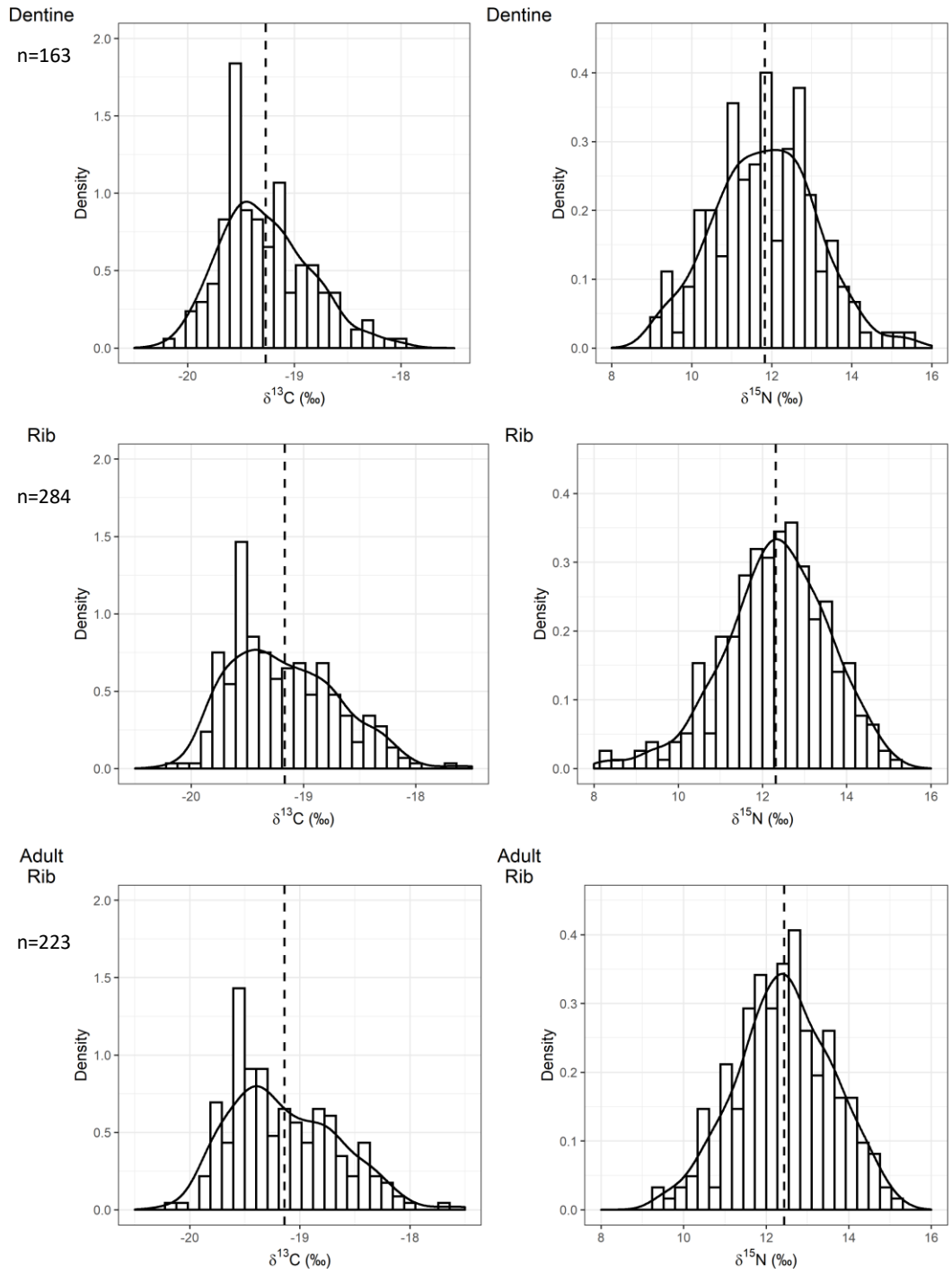


Figure 42: Histograms (with probability density) showing dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

ALL Human Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

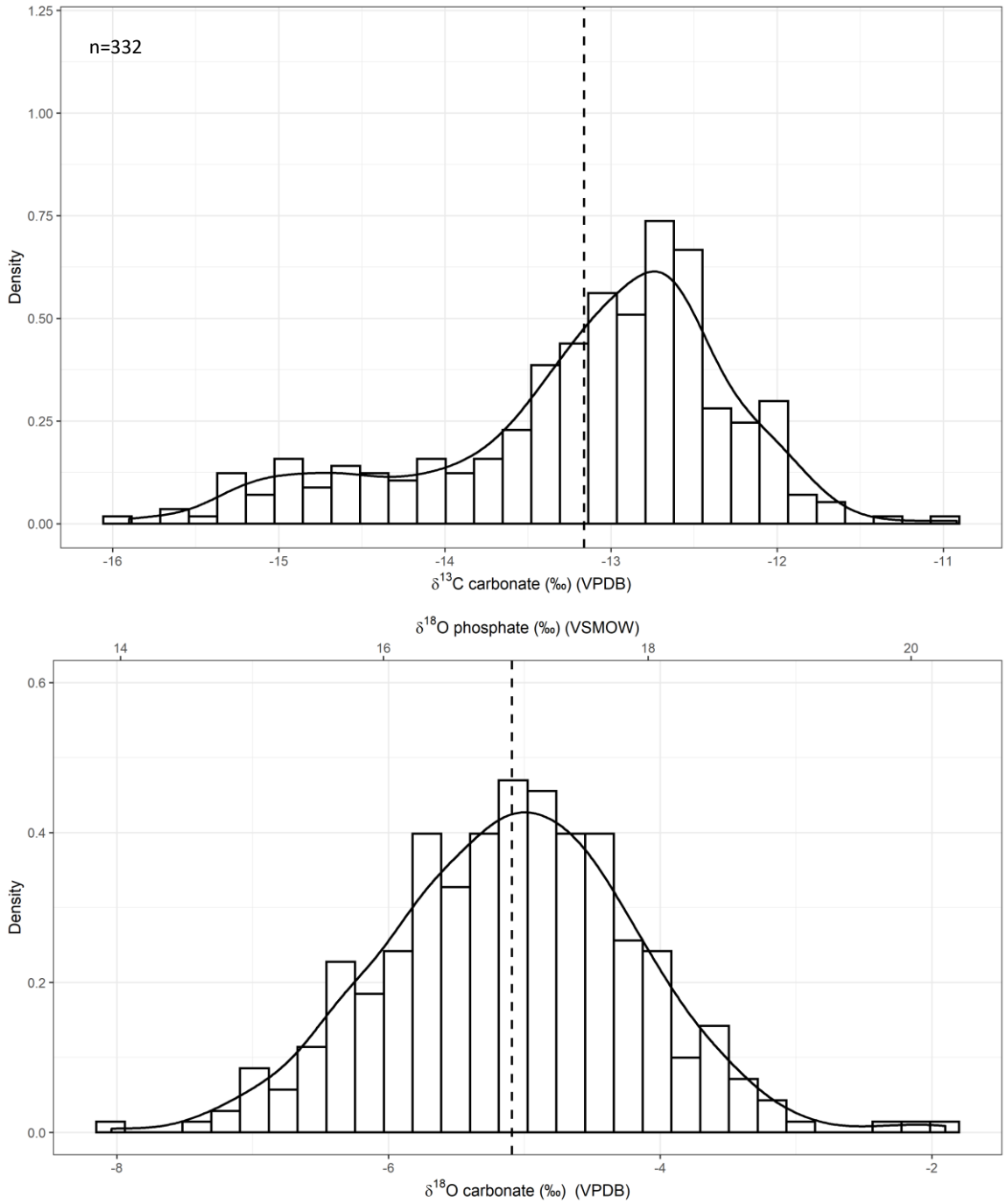


Figure 43: Histograms (with probability density) showing tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot

High/Late Medieval Human Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

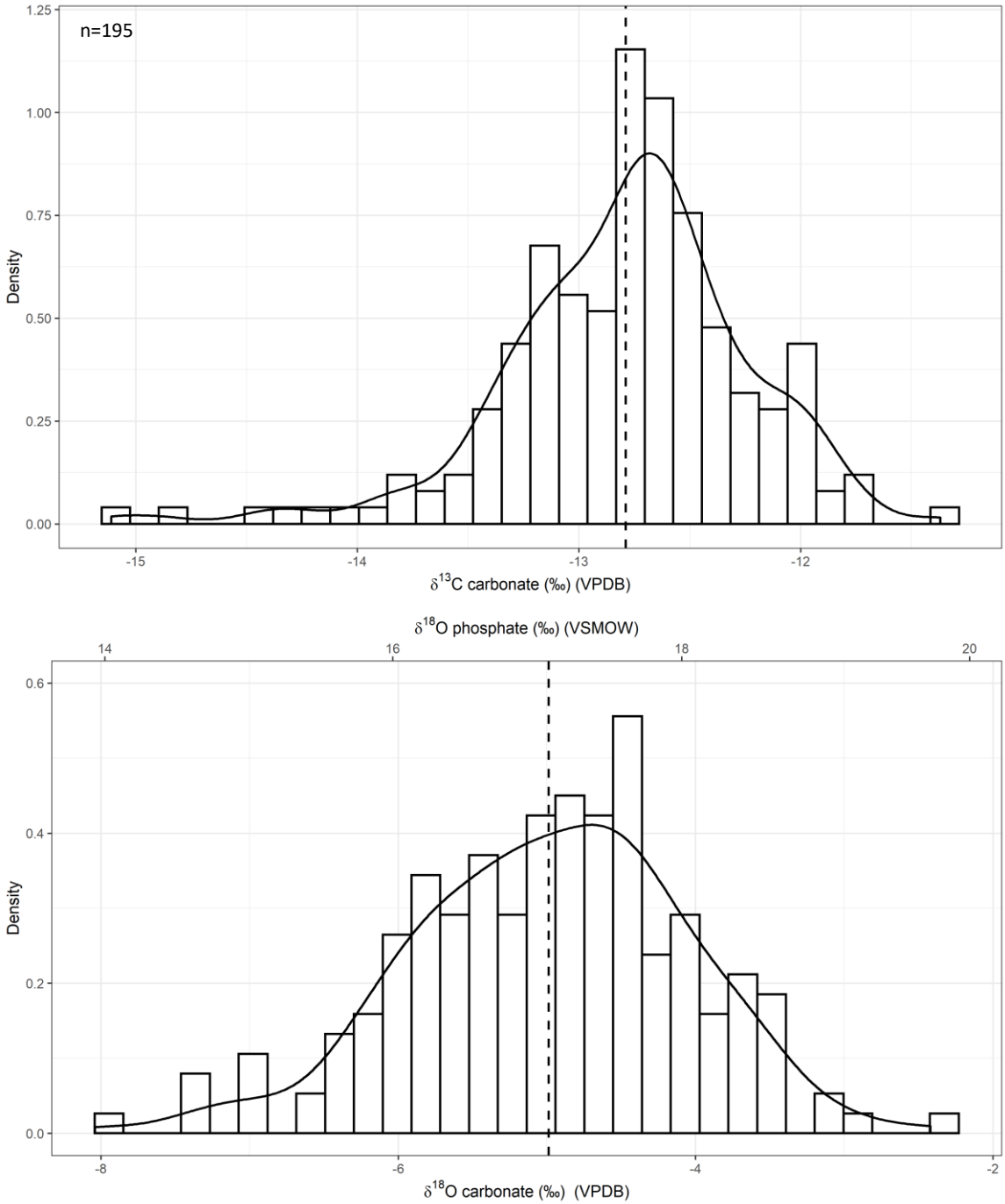


Figure 44: Histogram (with probability density) showing tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all High/Late Medieval Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

ALL Human Enamel $^{87}Sr/^{86}Sr$

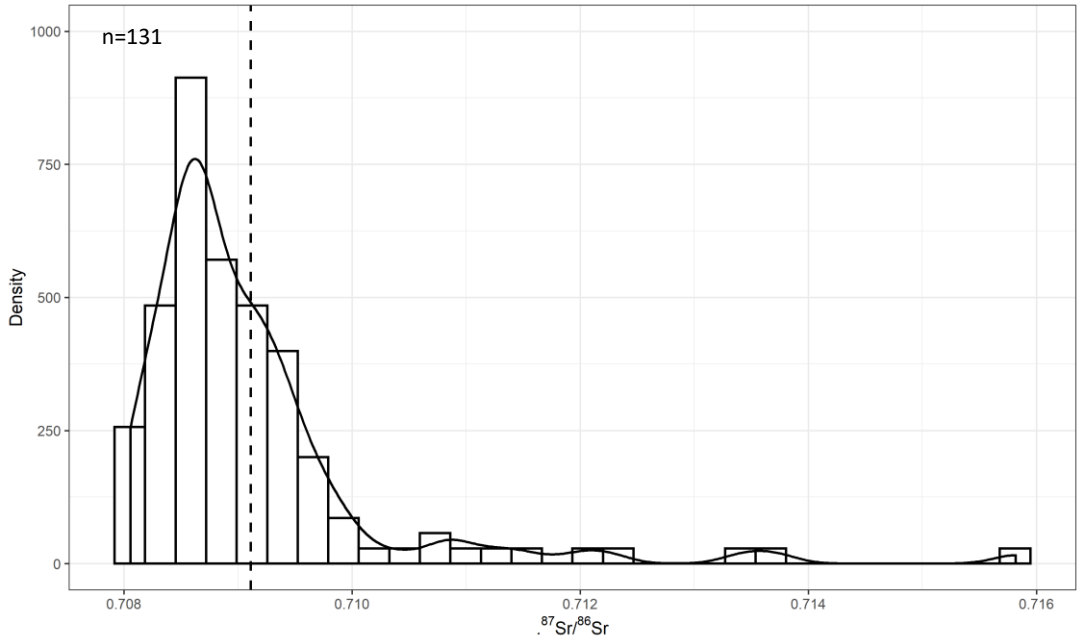


Figure 45: Histogram (with probability density) showing tooth enamel $^{87}Sr/^{86}Sr$ values for all Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in each plot

High/Late Medieval Human Enamel $^{87}Sr/^{86}Sr$

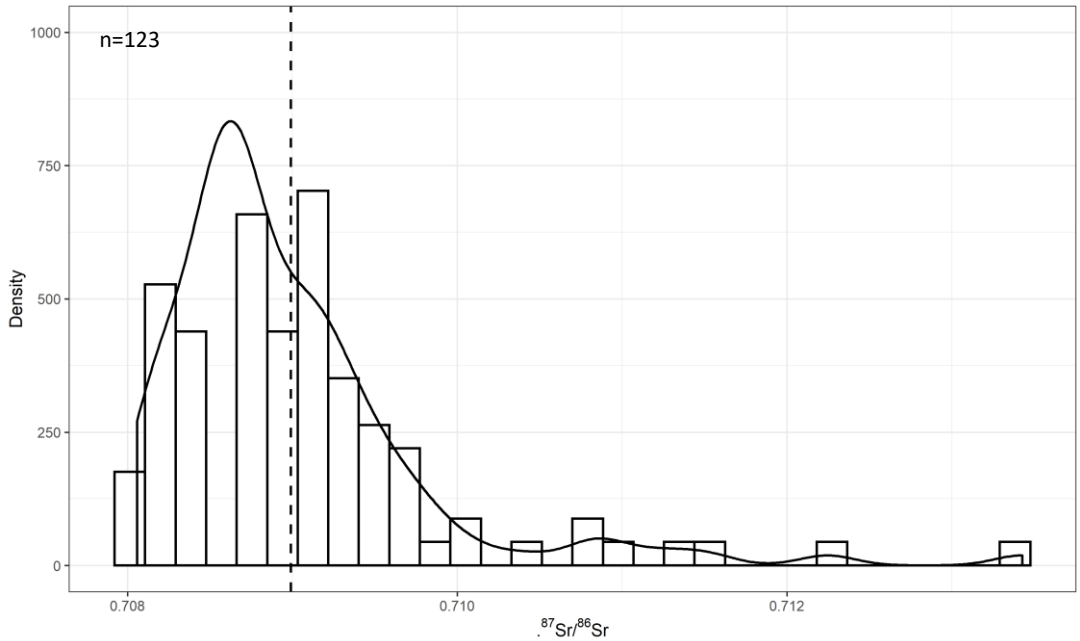


Figure 46: Histogram (with probability density) showing tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals analysed. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

6.3 Human Multi-Isotope Correlations

I investigated the correlation between the different human isotope results using the R package 'GGally' to produce a correlogram (Figure 47). The bottom left squares are scatterplots with a linear smoothing line, the middle diagonal squares are density plots, and the top right squares are Pearson correlation coefficients of each paired dataset. The strongest positive correlations occurred between rib collagen $\delta^{13}C$ and $\delta^{15}N$, as well as between rib and dentine $\delta^{13}C$ and rib and dentine $\delta^{15}N$. The correlation between $\delta^{13}C$ & $\delta^{15}N$ in dentine is not as positive as in rib, perhaps indicating differences in childhood and adult diet.

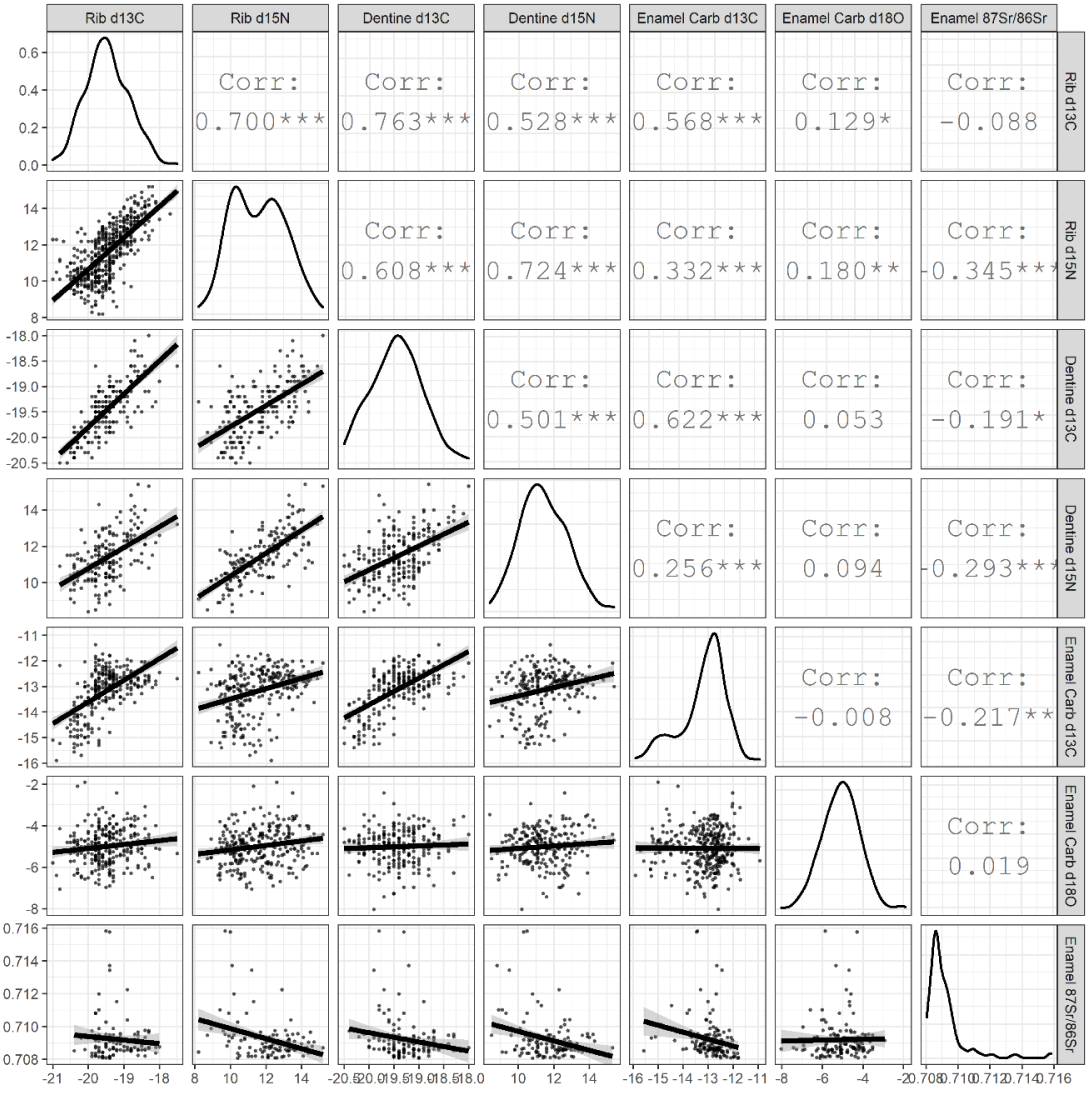


Figure 47: Correlogram consisting of scatterplots with linear smoothing lines, density plots and Pearson correlation coefficients for all types of human isotope data for all Cambridgeshire individuals analysed

6.4 Human Isotope Sample Demography

Figure 48 to Figure 51 illustrate the overall demography of the human individuals with successful isotope results. I aimed to sample each site approximately proportionate to the demographic of the skeletal collection available. Males consistently form the majority of sexed adults from almost every site except All Saints, making up approximately 60% of the sampled sexed adults for $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ analyses (Table 14). The sampling strategy was different for $^{87}Sr/^{86}Sr$ analysis, so the sex balance is more even, but males still form the majority (54%).

	Total Sexed Adults	***Number of Adult Females***	***% Female***	***Number of Adult Males***	***% Male***
Dentine collagen $\delta^{13}C$ & $\delta^{15}N$	**215**	90	42	125	58
Rib collagen $\delta^{13}C$ & $\delta^{15}N$	**370**	141	38	229	62
Enamel carbonate $\delta^{13}C$ & $\delta^{18}O$	**281**	113	40	168	60
Enamel $^{87}Sr/^{86}Sr$	**112**	52	46	60	54

Table 14: Total number of successful isotope results for sexed adults (>18yr), with the total number and percentage of adult females and males

The sampling prioritised adults, and so the non-adult (<18yr) sample is not representative of the non-adult population, and very young non-adults are almost completely absent from the sampled material. An attempt at sampling proportionately across the adult age categories in a similar manner to the sex categories was made, but this was more difficult due to the large number of categories and the quantity and type of material available. Figure 48 to Figure 51 show the differing age profiles at each site subgroup, with the Hospital detached cemetery having more younger age categories represented than many of the other High/Late Medieval sites. Comparable detailed age data was not collected for the Cambridgeshire datasets that were added to the primary dataset (Babraham, Melbourn Water Lane and Westfield Farm), so the demography by age is not included for those sites.

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



Figure 48: Demography of all Cambridgeshire individuals who produced successful dentine collagen $\delta^{13}C$ and $\delta^{15}N$ results

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

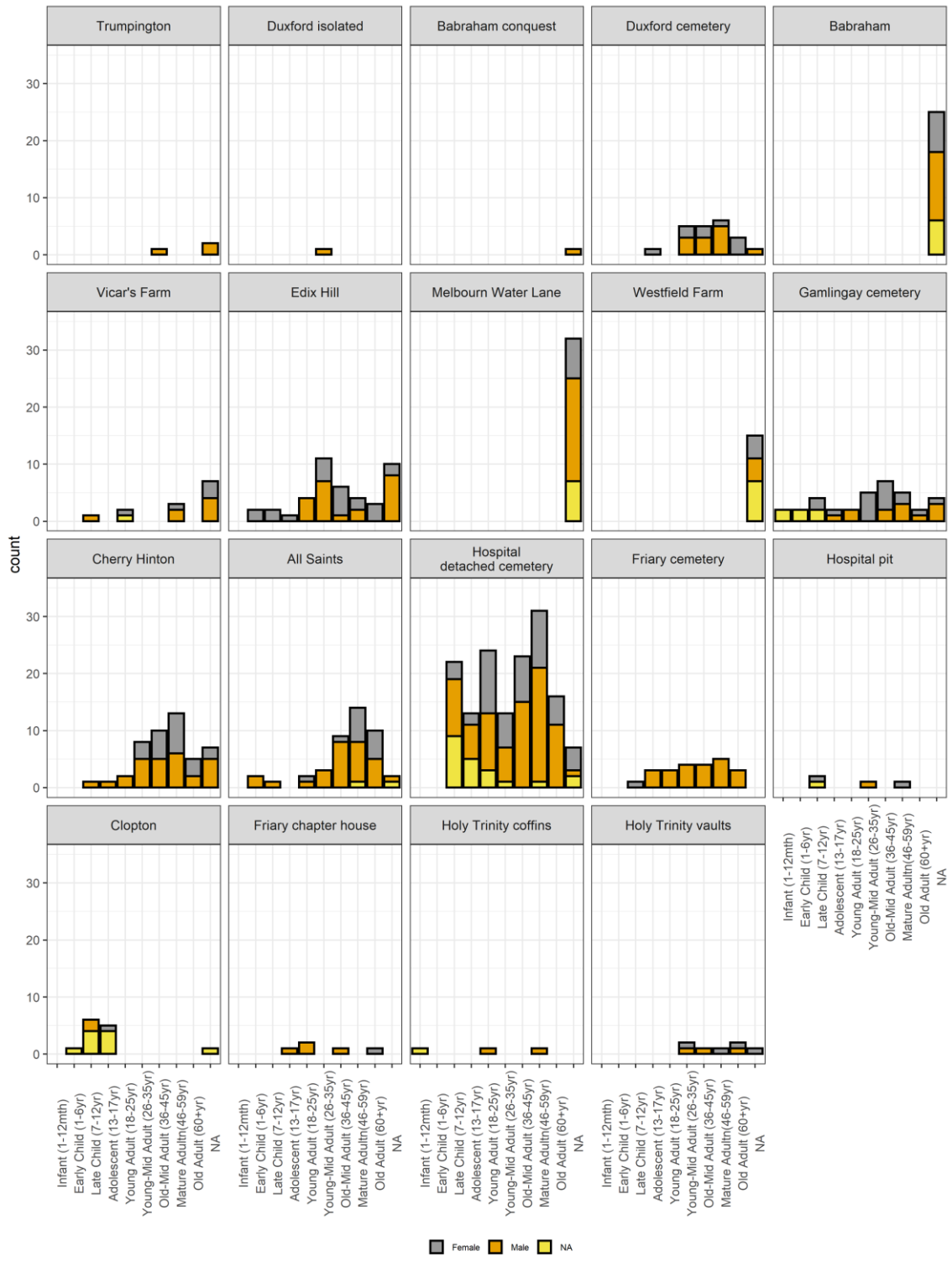


Figure 49: Demography of all Cambridgeshire individuals who produced successful rib collagen $\delta^{13}C$ and $\delta^{15}N$ results. Detailed age data for Babraham, Melbourn Water Lane and Westfield Farm was not collected.

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

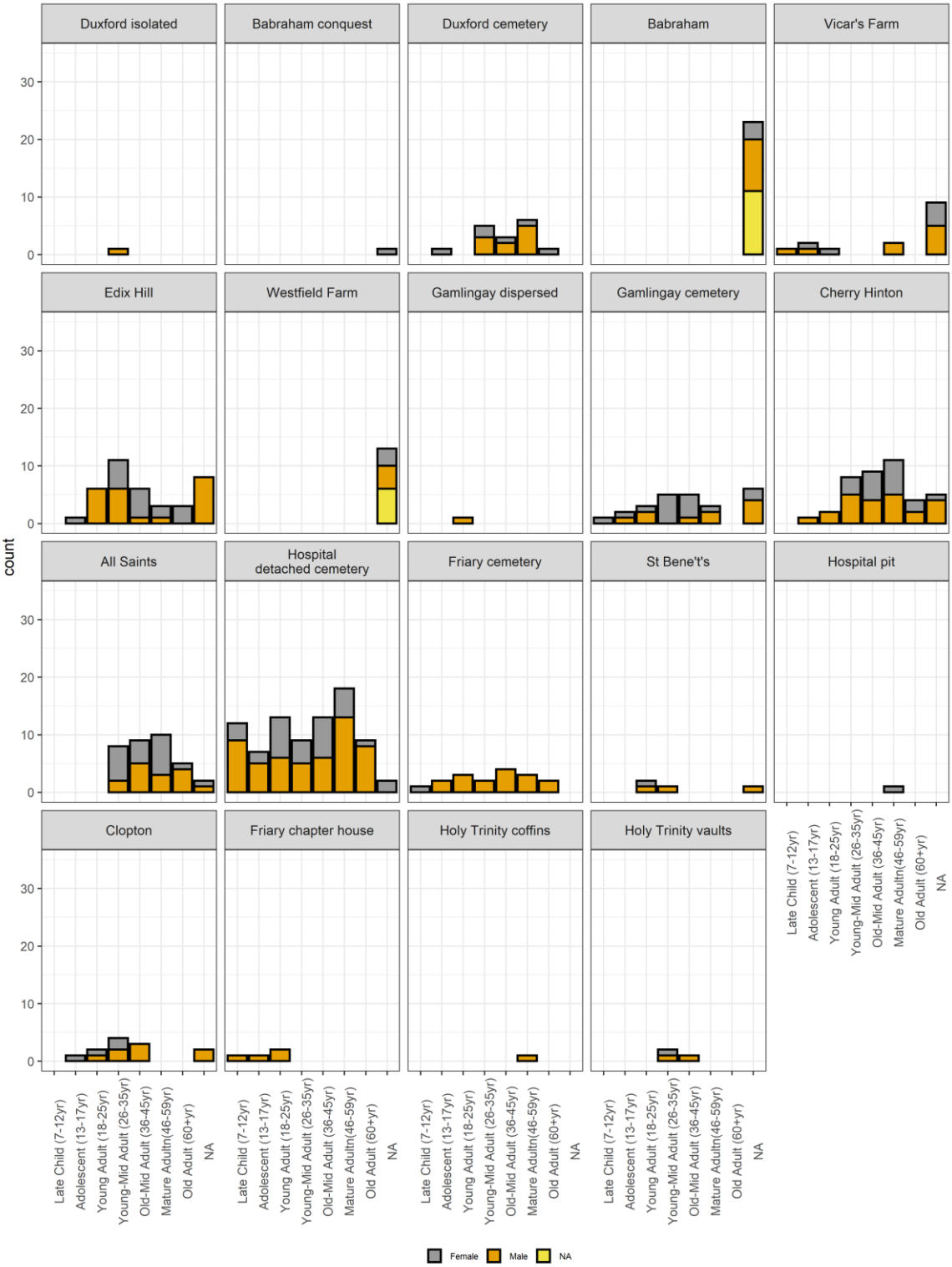


Figure 50: Demography of all Cambridgeshire individuals who produced successful enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ results

Enamel $^{87}Sr/^{86}Sr$

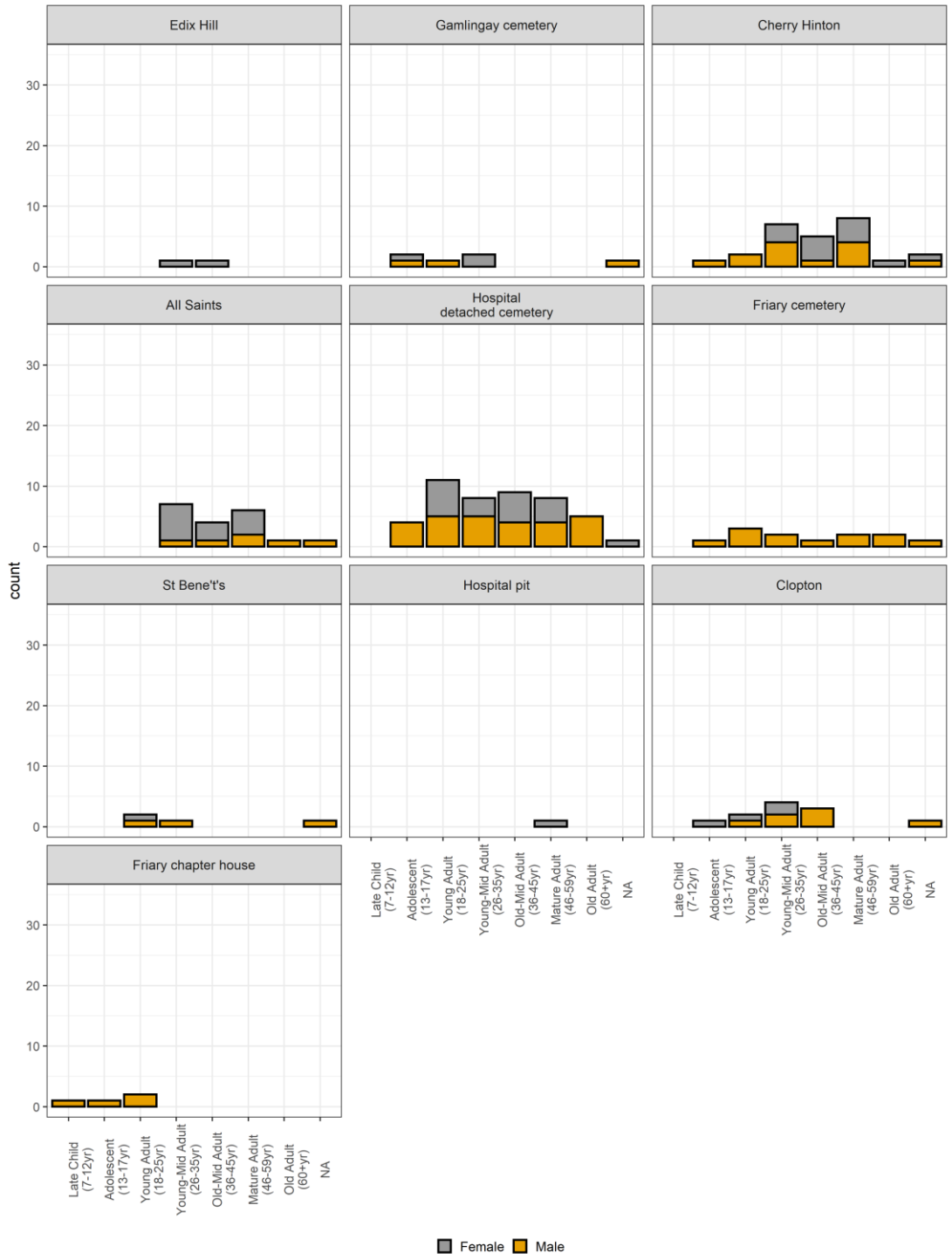


Figure 51: Demography of all Cambridgeshire individuals who produced successful enamel $^{87}Sr/^{86}Sr$ results

6.5 Summary of Data Quality and Character

The overwhelming majority of the samples taken for analysis of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ produced data which passed quality checks, resulting in a large isotope dataset for Cambridgeshire. Only c.77% of the samples taken for analysis $^{87}Sr/^{86}Sr$ produced usable results. As this was one of the first PhD projects in the Department of Archaeology, Cambridge to undertake 'in-house' strontium isotope analyses, a lower success rate may be expected as the methodology was still being developed. As with much archaeological data, the values do not necessarily follow a 'normal' distribution, and this is taken into account in further statistical analysis.



7. High/Late Medieval Isotope Results and Preliminary Discussion

Due to the large dataset, the results of the isotope analyses have been divided into two chapters: this chapter (7) focusses on the High/Late Medieval results, as this period is the focus of the thesis, while the next chapter (8) presents the results from across the longue durée and places the High/Late Medieval data in context with data spanning from the Neolithic to the Post-Medieval period.

This chapter presents the results of multi-tissue carbon, nitrogen, oxygen and strontium isotope analyses of High/Late Medieval human skeletal remains from archaeological sites in Cambridgeshire. This chapter also presents carbon and nitrogen isotope analyses of High/Late Medieval faunal bone. The results are investigated using summary statistics, explorative plots and further statistical tests to explore key trends in the isotope values which may inform questions regarding diet and mobility in High/Late Medieval Cambridge. Some preliminary discussion of the results and their implications are included in this chapter, but the key findings are discussed in more detail in Chapter 9. Full High/Late Medieval faunal and human isotope results can be found in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053), and summary statistics can be found in Appendix I. Accompanying scatterplots can be found in Appendix II. Where further statistical tests are used, corresponding full statistical analysis can be found in Appendix VI.

7. High/Late Medieval Isotope Results

This chapter will first present the faunal isotope results from the High/Late Medieval period in Cambridgeshire (Section 7.1). This is primarily to quantify the isotope values for each of High/Late Medieval faunal species analysed and to establish the 'isotopic baseline', characterising the local environment and potential variability (Makarewicz and Sealy 2015). Most importantly, the faunal isotope results are interrogated to assess whether there are meaningful differences in $\delta^{13}C$ & $\delta^{15}N$ values pre- and post-AD 1350, which may influence the interpretation of the human isotope values. The results are also used to determine that formally offsetting the human isotope values using the faunal baseline values is not required for the High/Late Medieval period, although it is required for the longue durée results, as discussed in Chapter 8.

The rest of this chapter investigates the human isotope data. To give the reader an initial overall impression of the results, Sections 7.2 and 7.3 include some interpretation and discussion to summarise overall characterisations of High/Late Medieval diet and mobility drawn from the data. Sections 7.4 to 7.9 then present the results in more detail by site subgroup, sex, social group and chronological divisions to assess whether meaningful differences can be seen in the values. As discussed in Section 4.5.3, the focus of the results is on adult individuals (>18yr) but these are not broken down further into specific age categories as this was deemed beyond the scope of the thesis. Specific questions to be addressed in this chapter include:

- To what extent can diet and protein contributions be characterised using $\delta^{13}C$ and $\delta^{15}N$ values?
- Are there meaningful differences between dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values?
- How many individuals are outliers, particularly for $\delta^{18}O$ and $^{87}Sr/^{86}Sr$?
- Are there meaningful differences in the numbers of individuals who are outliers between site subgroups and social groups?
- Are there meaningful differences in $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values between site subgroups?
- Are there meaningful differences in $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values by sex and/or social group?
- Are there meaningful differences in $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values pre- and post-AD 1350 or by Medieval century? Particularly, can differences presumed to be related to the Black Death be seen in the isotopes post-1350 e.g. changes in faunal $\delta^{13}C$ and $\delta^{15}N$ values due to changes in animal husbandry, increases in human $\delta^{15}N$ values related to increased animal protein consumption, more diversity in human $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values due to changes in population mobility?

Isotope values in this chapter are predominantly presented in one-dimension as violin and raincloud plots (see Section 5.4.2 for definitions). These plots show the distribution and range of the data, as well as outliers, allowing for visual comparisons between groups. $\delta^{13}C$ and $\delta^{15}N$ values are also presented together in scatterplots and bagplots where appropriate, either in the text, or in Appendix II. $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values are primarily discussed separately, with only some presentation of the values combined. This is due to several factors, but primarily due to the much larger scope and sample size for $\delta^{18}O$ values, and the ambiguity in interpreting $\delta^{18}O$ values compared to $^{87}Sr/^{86}Sr$ values. For $^{87}Sr/^{86}Sr$, interpreting means could be quite misleading and therefore medians and ranges are probably more indicative of the information required.

7.1 High/Late Medieval Faunal Isotope Results

To characterise the High/Late Medieval faunal 'isotopic baseline' for Cambridge, this section investigates the $\delta^{13}C$ and $\delta^{15}N$ values for key terrestrial and aquatic fauna. The faunal bones were recovered from Medieval contexts from central Cambridge and so it is hoped they represent the foods which people living in High/Late Medieval Cambridge may have eaten. The High/Late Medieval terrestrial faunal assemblage includes 20 bones from Saxo-Norman contexts dated to AD 900-1200 from St John's Triangle. These were included as the dates overlap more with the High Medieval than the Late Saxon period.

7.1.1 Characterisation of the High/Late Medieval Fauna Values

For terrestrial fauna, the isotopic mean, median and range differs between the taxa (Table 15, Figure 52). Overall, the isotopic range for cows and sheep/goats is very similar, although sheep/goats have higher mean $\delta^{15}N$ values (Figure 52). Pigs have higher mean $\delta^{13}C$ and $\delta^{15}N$ values than cows and sheep/goats (Table 15, Figure 52), although the enrichment in ^{15}N is not equivalent to a trophic level effect (Minagawa and Wada 1984). The chickens/domestic fowl are distinct in both $\delta^{15}N$ and $\delta^{13}C$, having a mean $\delta^{15}N$ value 2.7-3.0‰ higher than the cows and sheep/goats, indicating a trophic level increase and confirming their omnivory (Minagawa and Wada 1984, Bocherens and Drucker 2003) (Figure 52).

When broken down by site (New Museums and St John's Triangle), the mean $\delta^{13}C$ values are similar, if not identical, for each of the terrestrial fauna at both sites (Table 15). There are

differences in the mean $\delta^{15}N$ values between the sites, particularly for cows, where there is a 1.0‰ difference in the means (Table 15). This may indicate differences in meat procurement at these sites. As the faunal data is being used in this thesis as a representation of the isotope values of potential food sources for individuals living in High/Late Cambridge, this variation is interesting, and combining the data from the two sites into a general representation of available High/Late Medieval fauna embraces this variation.

As much of the research concerning differences between human and faunal isotope values relates to assessment of trophic level, it was deemed useful to also combine the cow and sheep/goat data to provide general 'herbivore' isotope values (Table 15). Figure 53 shows the herbivore data is relatively evenly distributed around the depth median, there are no outliers, and data from the two sites overlap. This indicates that combining the data provides a relatively good, if crude, herbivore isotopic signature for High/Late Medieval Cambridge, embracing the variation in available food sources.

There are extremely large differences in the isotope values of the different fish taxa (Table 15, Figure 52). These largely follow expectations based on their environment and trophic level (see Chapter 2). The marine fish (cod, flatfish, herring and ling) are clearly distinguished from the other fish by their less negative $\delta^{13}C$ values. The summary statistics and analysis for the fish is limited by the small sample size for each species, but for cod, where a larger sample size is available, it is clear there is a large range in both the $\delta^{13}C$ and $\delta^{15}N$ values, perhaps indicating variation in their source (Orton *et al.* 2011, Fuller *et al.* 2012).

Taxon	*Site*	*n*	Bone Collagen $\delta^{13}C$ (‰) (VPDB)						Bone Collagen $\delta^{15}N$ (‰) (AIR)					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Chicken/ Domestic Fowl	**ALL**	**25**	-20.2	0.4	-20.1	-21.1	-19.4	1.7	10.4	1.5	10.4	7.4	14.1	6.7
	New Museums Site	10	-20.2	0.3	-20.1	-20.7	-19.7	1.0	10.2	1.3	10.4	8.0	12.3	4.3
	St John's Triangle	15	-20.2	0.4	-20.1	-21.1	-19.4	1.7	10.5	1.6	10.2	7.4	14.1	6.7
Cow	**ALL**	**30**	-21.7	0.4	-21.5	-22.5	-21.0	1.5	7.4	1.4	7.3	5.0	10.1	5.1
	New Museums Site	15	-21.6	0.3	-21.5	-22.5	-21.2	1.3	7.9	1.4	7.9	5.5	10.1	4.6
	St John's Triangle	15	-21.7	0.4	-21.5	-22.4	-21.0	1.4	6.9	1.4	6.6	5.0	9.4	4.4
Pig	**ALL**	**30**	-21.1	0.5	-21.0	-22.1	-20.4	1.7	7.9	1.5	8.5	4.5	11.5	7.0
	New Museums Site	15	-21.1	0.5	-21.0	-22.1	-20.4	1.7	8.1	1.4	8.6	5.8	10.0	4.2
	St John's Triangle	15	-21.1	0.4	-21.0	-21.8	-20.5	1.3	7.8	1.7	7.9	4.5	11.5	7.0
Sheep/ Goat	**ALL**	**30**	-21.7	0.4	-21.7	-22.8	-20.8	2.0	7.7	1.3	7.7	5.0	10.3	5.3
	New Museums Site	15	-21.7	0.5	-21.7	-22.2	-20.8	1.4	7.8	1.3	7.8	5.0	10.1	5.1
	St John's Triangle	15	-21.7	0.4	-21.6	-22.8	-21.2	1.6	7.5	1.3	7.4	5.6	10.3	4.7
[Herbivores-combined cow and sheep/goat]	***ALL***	*60*	-21.7	0.4	-21.6	-22.8	-20.8	2.0	7.5	1.4	7.6	5.0	10.3	5.3
	New Museums Site	*30*	-21.7	0.4	-21.6	-22.5	-20.8	1.7	7.9	1.3	7.9	5.0	10.1	5.1
	St John's Triangle	*30*	-21.7	0.4	-21.6	-22.8	-21.0	1.8	7.2	1.4	7.0	5.0	10.3	5.3
Cod	**ALL**	**22**	-13.1	0.8	-13.1	-15.2	11.8	3.4	15.6	1.1	15.6	13.2	17.6	4.4
	Corpus Christi	1	-13.8	-	-13.8	-13.8	-13.8	-	15.6	-	15.6	15.6	15.6	-
	Eastern Gate Hotel	5	-12.9	0.4	-13.0	-13.3	-12.4	0.9	16.4	0.8	16.7	14.9	17.0	2.1
	Grand Arcade	9	-12.7	0.8	-12.9	-13.9	-11.8	2.1	15.8	0.8	15.7	15.1	17.6	2.5
	Hostel Yard Corpus Christi	3	-14.3	0.9	-14.3	-15.2	-13.4	1.8	14.9	1.2	14.4	14.0	16.3	2.3
	St John's Triangle	4	-13.1	0.5	-13.1	-13.5	-12.5	1.0	14.4	1.1	14.3	13.2	15.8	2.6
Cyprinid	*Eastern Gate Hotel*	**2**	-19.7	0.5	-19.7	-20.1	-19.4	0.7	10.9	0.2	10.9	10.7	11.1	0.4
Eel	*Eastern Gate Hotel*	**2**	-24.2	0.4	-24.2	-24.5	-23.9	0.6	12.1	3.0	12.1	10.0	14.2	4.2
Flatfish	**ALL**	**2**	-11.9	0.1	-11.9	-12.0	-11.8	0.2	13.8	1.3	13.8	12.9	14.7	1.8
	Corpus Christi	1	-12.0	-	-12.0	-12.0	-12.0	-	14.7	-	14.7	14.7	14.7	-
	Eastern Gate Hotel	1	-11.8	-	-11.8	-11.8	-11.8	-	12.9	-	12.9	12.9	12.9	-
Herring	*Eastern Gate Hotel*	**4**	-14.8	0.5	-14.8	-15.3	-14.4	0.9	10.9	0.2	10.9	10.7	11.2	0.5
Ling	*Eastern Gate Hotel*	**1**	-11.5	-	-11.5	-11.5	-11.5	0.0	17.9	-	17.9	17.9	17.9	-
Pike	*Eastern Gate Hotel*	**1**	-23.4	-	-23.4	-23.4	-23.4	-	14.3	-	14.3	14.3	14.3	-
TOTAL TERRESTRIAL		**115**												
TOTAL FISH		**34**												

Table 15: Summary statistics for bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from all High/Late Medieval Cambridgeshire fauna analysed, by site

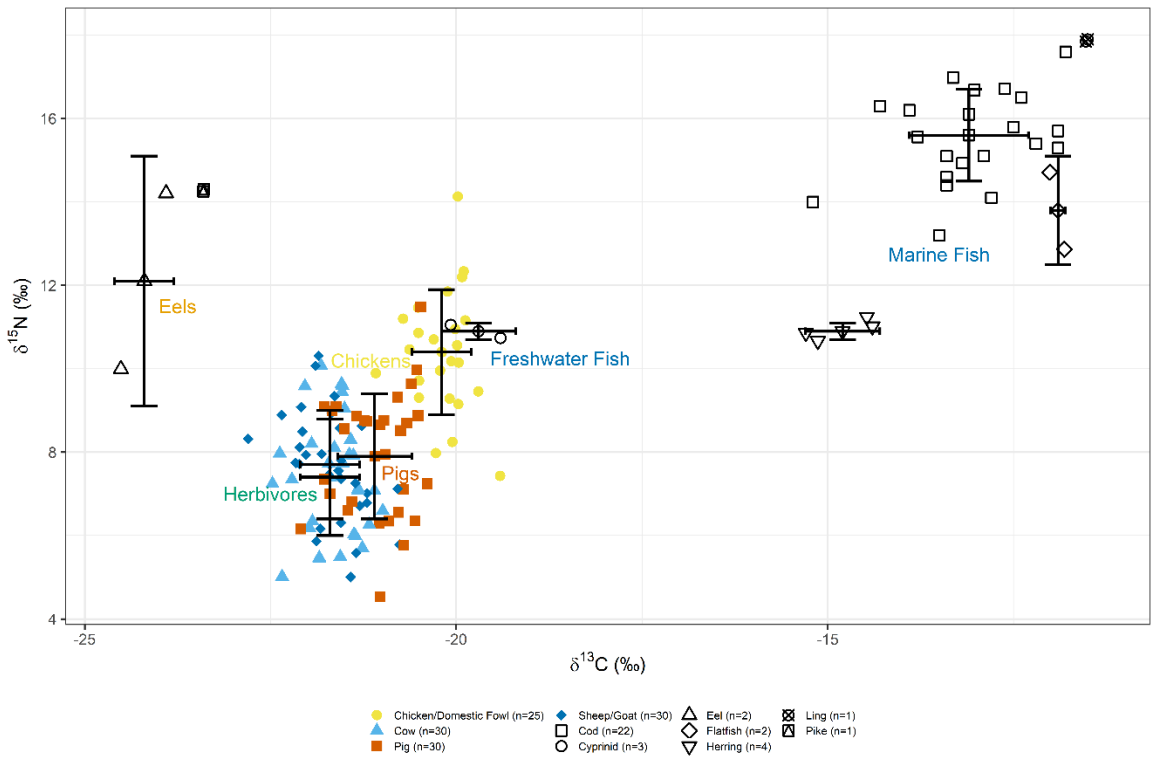


Figure 52: Scatterplot showing mean and individual bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire fauna analysed. Error bars indicate 1 SD from the mean.

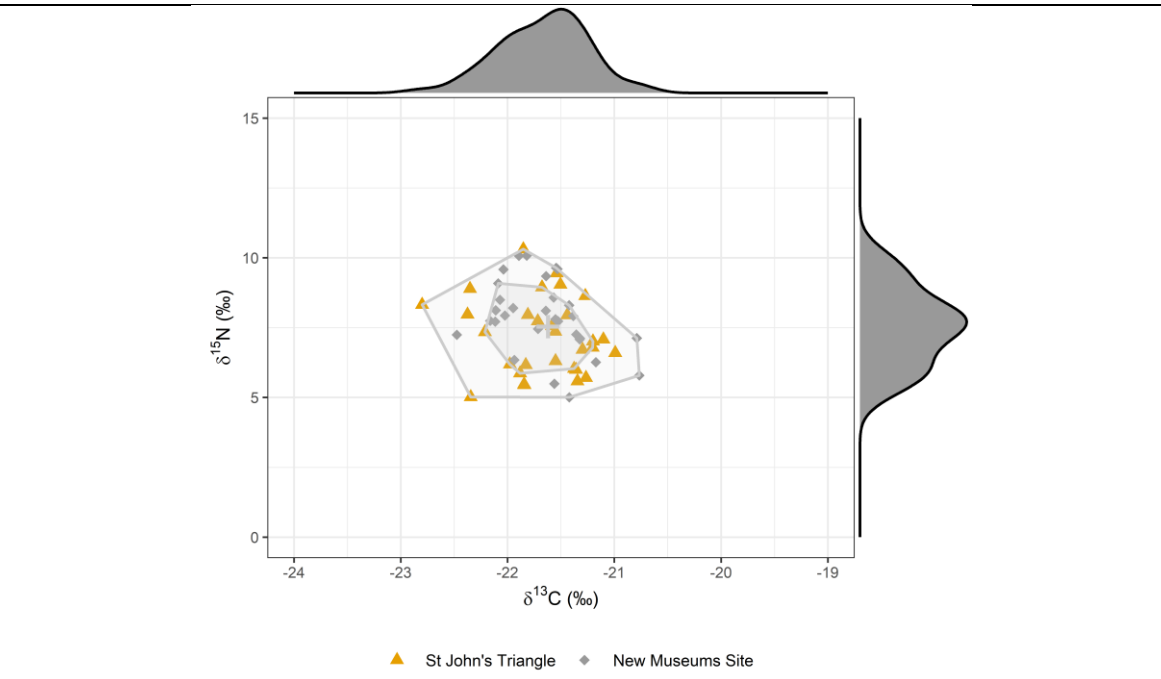


Figure 53: Bagplot with scatterplot and marginal density showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval combined domestic herbivores (cows and sheep/goats) analysed from Cambridgeshire sites

7.1.2 High/Late Medieval Faunal Isotope Results by Pre- or Post-AD 1350

To assess whether there were significant changes in the faunal isotopic signature after the Black Death, the faunal isotope data from the High/Late Medieval period was divided into pre- or post-1350 date categories. This is a very crude method and obviously many other factors could influence differences in these categories, however, it provides some sense of the magnitude of change. Pre/post-1350 comparisons were only performed for terrestrial fauna, as there were no suitably dated fish for a comparison. **95** terrestrial faunal bones analysed from High/Late Medieval contexts could be assigned to a pre-1350 or post-1350 date category. In this case, the 20 faunal bones from the Saxo-Norman contexts from St John's Triangle were excluded as their slightly earlier date could skew the pre-1350 category and could mask patterns relating to changes in the later periods.

There appears to be little notable difference in pre/post-1350 mean $\delta^{13}C$ values for each terrestrial taxon but there is a much greater difference in pre/post-1350 mean $\delta^{15}N$ values (Table 16, Figure 54). All taxa show a difference between their pre/post-1350 mean $\delta^{15}N$ of >0.6‰, with pigs showing an increase of 1.7‰ and a much greater range in their post-1350 values. Although sheep/goats show a post-1350 increase in mean $\delta^{15}N$ values of 0.7‰, cows show a decrease of 0.6‰, so when the domestic herbivores (cows and sheep/goats) are combined, there is no difference in the mean $\delta^{13}C$ and $\delta^{15}N$ values pre/post-1350 (Figure 55, Figure 56). The lack of difference between the mean pre- and post-1350 $\delta^{13}C$ and $\delta^{15}N$ values for the combined domestic herbivores is also demonstrated by Welch's T-Test ($\delta^{13}C$: p=0.914, $\delta^{15}N$: p=0.986).

While the small post-1350 sample size severely limits interpretation, on a taxa level, the data may indicate changes in animal husbandry post-1350. However, as the changes in isotope values are not all in the same direction, this cannot be simply attributed to one factor, such as increased crop manuring in the later period (Bogaard *et al.* 2007). Also, as demonstrated in Table 15, there are differences between the $\delta^{15}N$ values by site, and the apparent pre/post-1350 changes could be partially due to the fact the post-1350 sample is from St John's Triangle only. Despite these changes, as humans were likely to be eating a combination of these animals (see Chapter 2), the effective 'cancelling out' of the changes in herbivore values means that

pre/post-1350 faunal changes are unlikely to have had a great effect, or at least an effect that can be teased apart from other factors, on the human isotope values.

Taxon	***Pre or Post 1350***	***n***	**Bone Collagen $\delta^{13}C$ (‰) (VPDB)**						**Bone Collagen $\delta^{15}N$ (‰) (AIR)**					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Chicken/ Domestic Fowl	Pre	15	-20.1	0.3	-20.1	-20.7	-19.7	1.0	10.4	1.3	10.5	8.0	12.3	4.3
	Post	5	-20.3	0.3	-20.3	-20.5	-20.0	0.5	11.3	1.8	10.9	9.2	14.1	4.9
Cow	Pre	19	-21.6	0.4	-21.5	-22.5	-21.1	1.4	7.6	1.4	7.7	5.5	10.1	4.6
	Post	6	-21.8	0.4	-21.7	-22.3	-21.3	1.0	7.0	1.9	6.5	5.0	9.4	4.4
Pig	Pre	20	-21.0	0.5	-21.0	-22.1	-20.4	1.7	7.7	1.5	8.3	4.5	10.0	5.5
	Post	5	-21.1	0.6	-21.0	-21.8	-20.5	1.3	9.4	1.2	9.1	8.5	11.5	3.0
Sheep/Goat	Pre	20	-21.7	0.5	-21.7	-22.8	-20.8	2.0	7.8	1.3	7.8	5.0	10.1	5.1
	Post	5	-21.6	0.3	-21.7	-21.9	-21.2	0.7	8.5	1.3	8.6	6.8	10.3	3.5
TOTAL		**95**												
[Herbivores – combined cow and sheep/goat values]	*Pre*	*39*	-21.7	0.4	-21.6	-22.8	-20.8	2.0	7.7	1.3	7.7	5.0	10.1	5.1
	Post	*11*	-21.7	0.4	-21.7	-22.3	-21.2	1.1	7.7	1.8	8.0	5.0	10.3	5.3

Table 16: Summary statistics for bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from all High/Late Medieval Cambridgeshire domestic terrestrial fauna analysed, by pre/post-1350

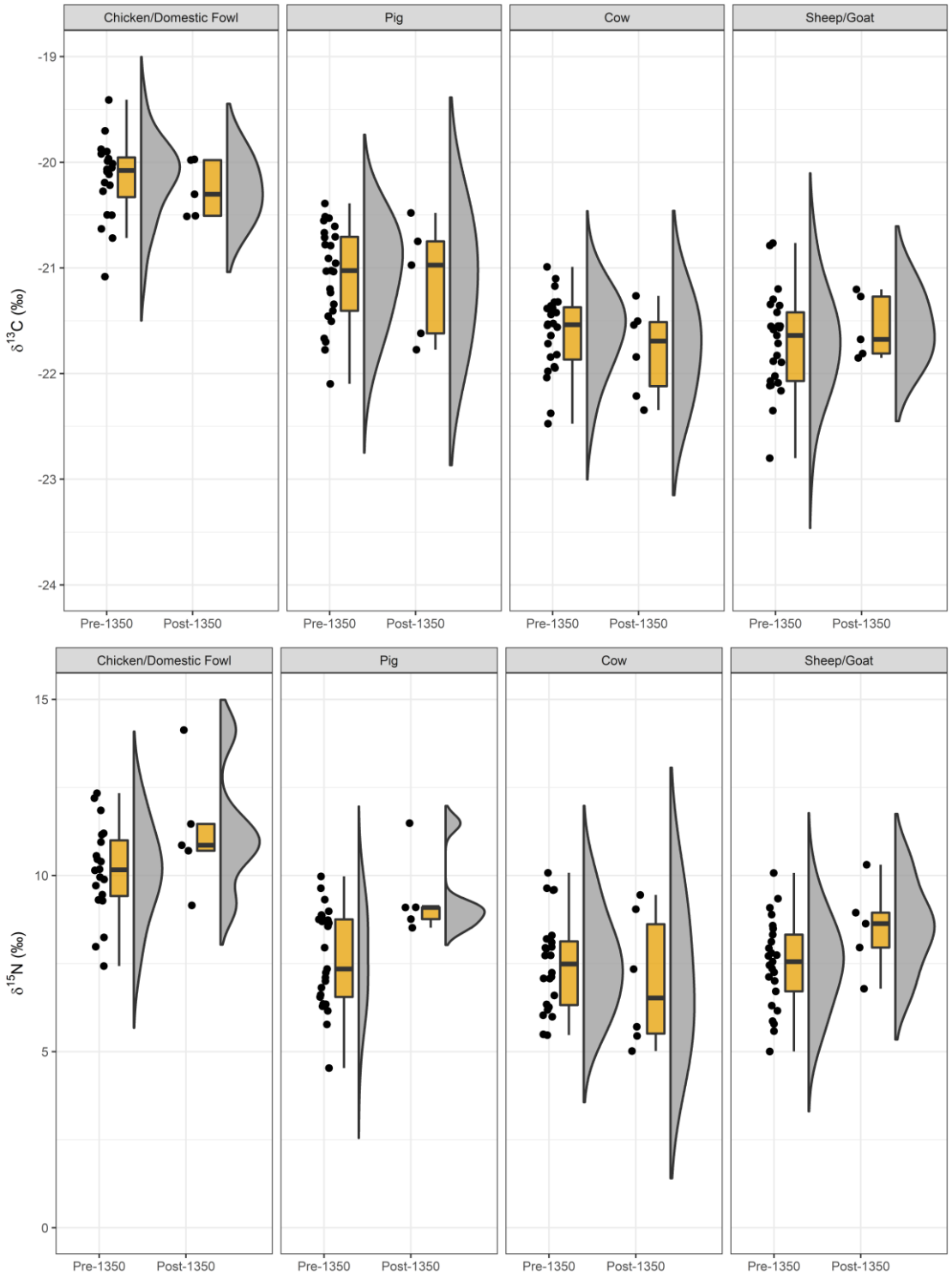


Figure 54: Raincloud plots showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval domestic terrestrial fauna analysed from Cambridgeshire sites, by pre/post-1350

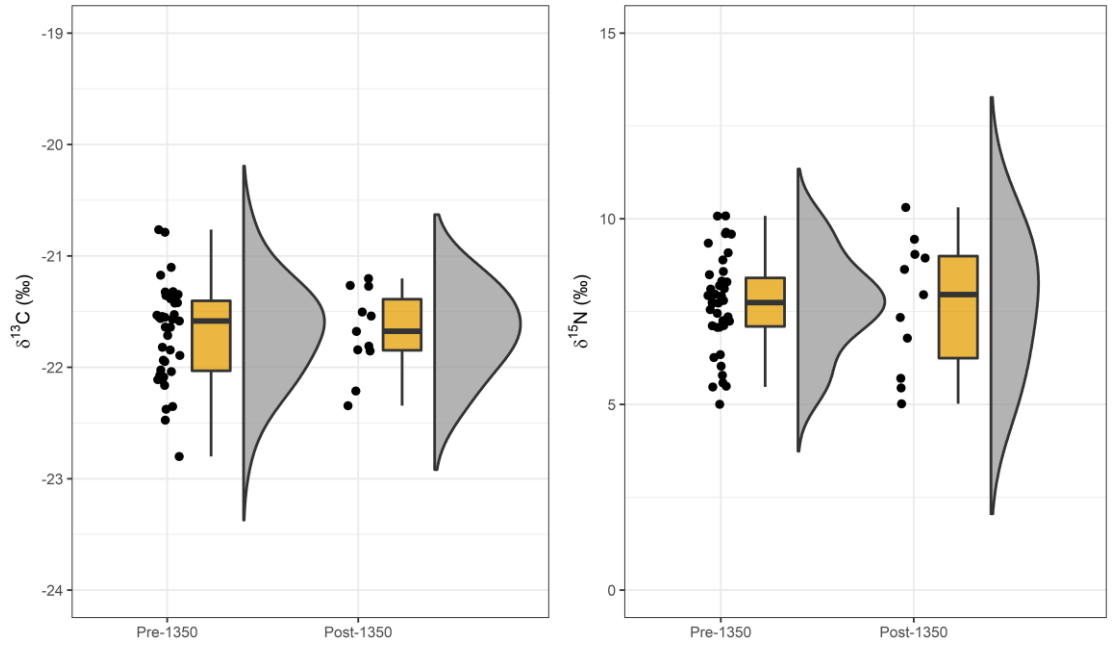


Figure 55: Raincloud plots showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval domestic herbivores (cow, sheep/goats) analysed from Cambridgeshire sites, by pre/post-1350

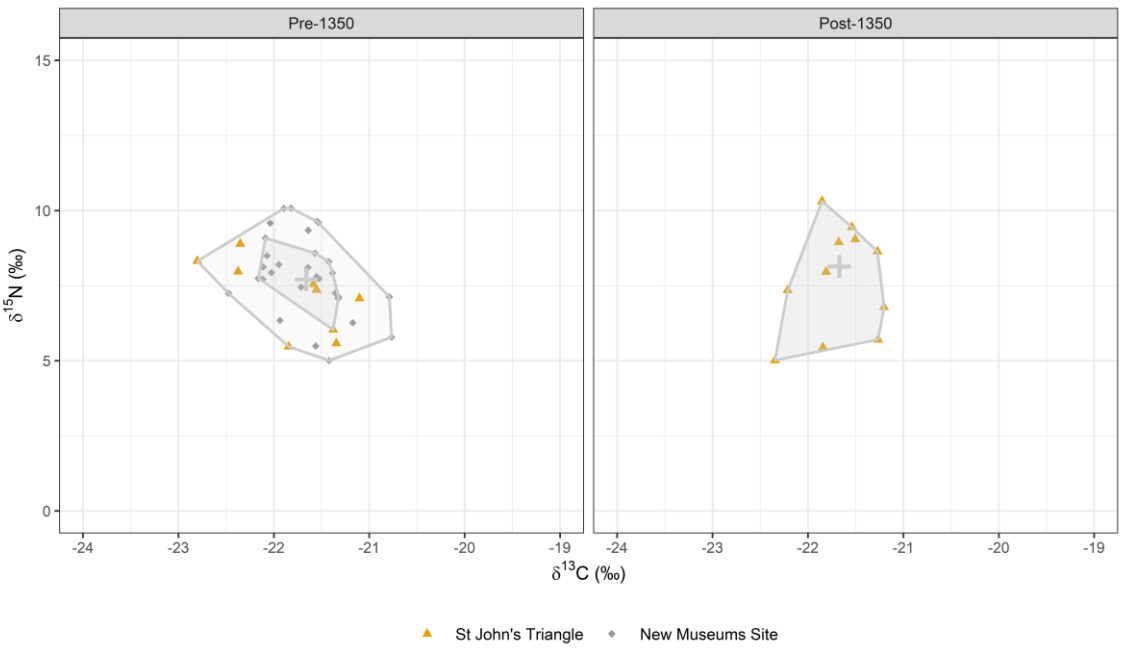


Figure 56: Bagplots with scatterplots showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval domestic herbivores (cow, sheep/goats) analysed from Cambridgeshire sites, by pre/post-1350

7.1.3 Summary of High/Late Medieval Faunal Isotope Results

This section has demonstrated the range of isotope values present in the High/Late Medieval faunal assemblage. This is important for subsequent interpretations of terrestrial and aquatic protein consumption, trophic level and temporal changes in the human isotope data, although it should be noted that the faunal data was sourced from a small number of town sites and may not be fully representative of the diet available to all the High/Late Medieval human individuals in the Cambridgeshire sample. The similarity in $\delta^{15}N$ values observed in the pigs and the domestic herbivores (cow, sheep/goat), as well as the relatively high $\delta^{15}N$ values in the chickens are important findings. This may affect interpretations of $\delta^{15}N$ values in humans, as relatively low $\delta^{13}C$ but high $\delta^{15}N$ values in humans is sometimes attributed to the consumption of pork from omnivorous pigs with high $\delta^{15}N$ values (e.g. Müldner and Richards 2007b, p. 695), but the similarity in pig and herbivore isotope values means this may not be detectable here. Another important finding for further interpretations is the overall lack of meaningful change in the herbivore $\delta^{13}C$ and $\delta^{15}N$ values pre/post-1350. While there are other changes in the faunal isotope data, which will need to be considered, this lack of change in the herbivore baseline means that potential pre/post-1350 changes in human isotope values may not be due to underlying changes in faunal isotope values.

In particular, an aim of this section was to establish if pre/post-1350 variability in the faunal isotope baseline was so large that it would need to be formally taken into account when analysing the human data, for example by calculating human-herbivore offset values (e.g. Lightfoot *et al.* 2012, 2015, Müldner 2013) (see Section 8.2 for further explanation). As the High/Late Medieval human isotope data is relatively geographically and temporally constrained, and the faunal isotope data does not indicate large changes in the herbivore isotope baseline, I decided that the High/Late Medieval human isotope data in the subsequent sections in this chapter could be analysed without calculating human-herbivore offset carbon and nitrogen values, as employed later in Chapter 8.

7.2 Overall Characterisation of High/Late Medieval Diet

Generally, the High/Late Medieval individuals are enriched in ^{15}N compared to the herbivorous and omnivorous domestic animals sampled and trend towards the marine fish (Figure 57). This enrichment over the contemporary herbivores indicates the High/Late Medieval individuals held a higher trophic position, consuming animal proteins enough to increase the $\delta^{15}N$ values present in their dentine and rib collagen (Bocherens and Drucker 2003). There is a wide spread in the data, with some individuals having high $\delta^{15}N$ and $\delta^{13}C$ values, which could indicate varying access to and consumption of marine proteins (Minagawa and Wada 1984, Schoeninger and DeNiro 1984, Müldner *et al.* 2009). The rib collagen data generally has a wider range than the dentine data, with higher $\delta^{15}N$ values, indicating differences between childhood and adult diets (Sealy *et al.* 1995, Kancle *et al.* 2018). Overall, the $\delta^{13}C$ values for the High/Late Medieval individuals are relatively negative, indicating a predominantly C_3, rather than C_4 plant-based diet (O'Leary 1981, van der Merwe 1991, Lee-Thorp 2008). No individuals have $\delta^{13}C$ values indicative of C_4 plant consumption, indicating that people in High/Late Medieval Cambridge were not eating C_4 foods, or at least not in detectable amounts.

Overall, an initial summary of the $\delta^{13}C$ and $\delta^{15}N$ values indicate that most High/Late Medieval people in Cambridge were omnivorous. The diet was characterised by the consumption of C_3 plants, terrestrial animal proteins and variable proportions of marine fish, and may have differed between childhood and adulthood. High/Late Medieval diet is discussed in more detail in Chapter 9, Section 9.2.

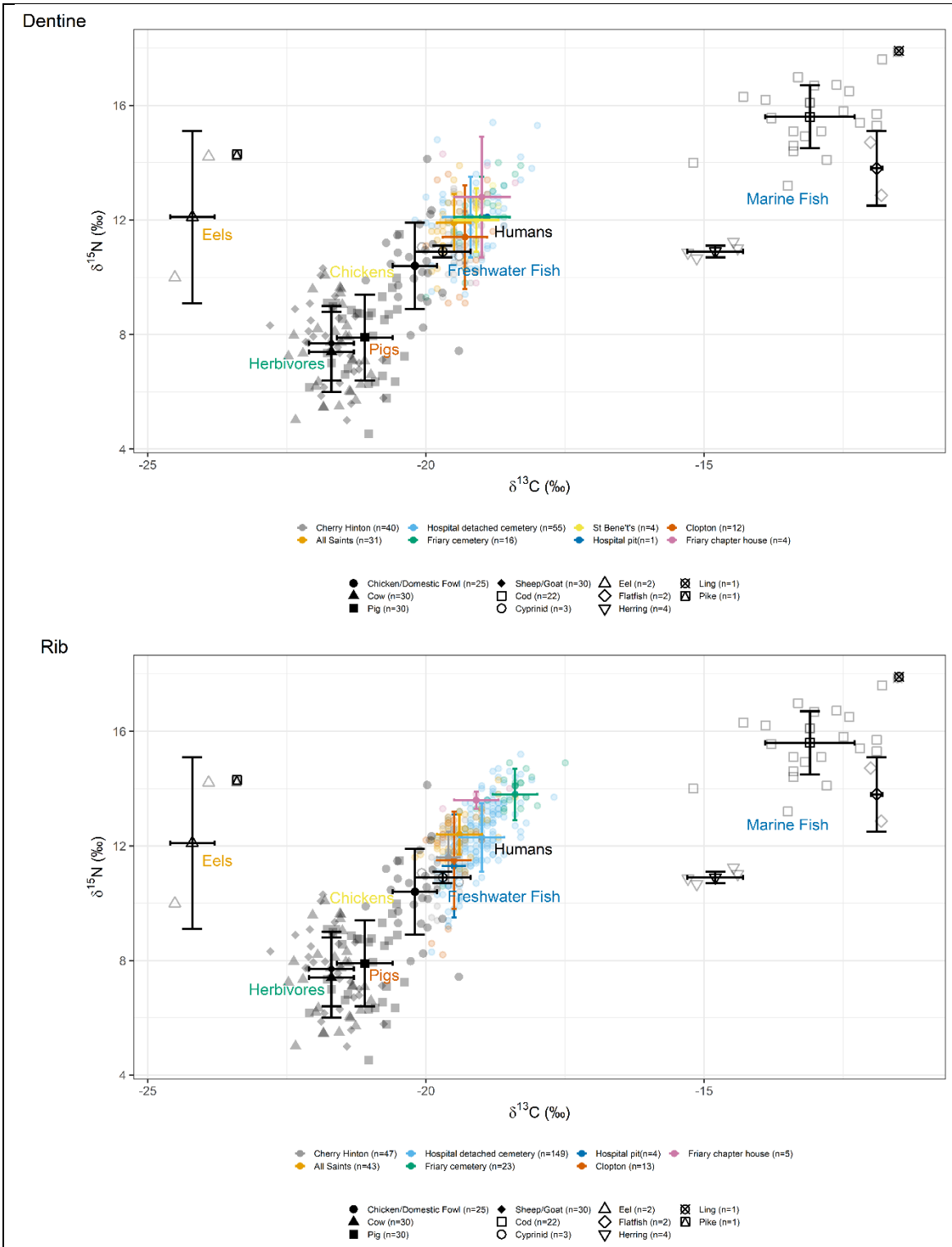


Figure 57: Scatterplots showing mean and individual dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals analysed (by overall site), with mean and individual bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire fauna analysed. Error bars indicate 1 SD from the mean.

7.2.1 Characterisation of High/Late Medieval Diet: Considering Carbonate Carbon and Collagen Carbon

As discussed in Chapter 3, $\delta^{13}C$ in collagen is assumed to preferentially reflect dietary protein, whereas $\delta^{13}C$ in bioapatite is assumed to be more reflective of whole diet (Ambrose and Norr 1993, Tieszen and Fagre 1993) (although this is complicated by differential amino acid routing (Jim *et al.* 2004, 2006, Webb *et al.* 2017)). Therefore calculations of enamel carbonate-dentine collagen $\Delta^{13}C$ ($\Delta^{13}C_{carb\text{-}coll}$) values may reveal further information about diet during tooth formation (Kusaka *et al.* 2015). Calculations show that that Cherry Hinton has the highest mean $\Delta^{13}C_{carb\text{-}coll}$ value whereas the Friary cemetery has the lowest (Table 17). Plotting $\Delta^{13}C_{carb\text{-}coll}$ values against dentine collagen $\delta^{15}N$ values shows differences in the spread of the data between the site subgroups, highlighting the larger range in the $\Delta^{13}C_{carb\text{-}coll}$ values at the Hospital detached cemetery (Figure 58). Clementz *et al.* (2009) have reported mean $\Delta^{13}C_{bioapatite\text{-}collegen}$ values for various mammals: terrestrial carnivores (4.8±0.4‰), terrestrial herbivores (7.6±0.5‰), marine carnivores (3.6±1.0‰) and marine herbivores (7.8‰±1.2) indicating diets containing terrestrial proteins are likely to generally exhibit lower $\Delta^{13}C_{carb\text{-}coll}$ values than herbivorous diets and low $\Delta^{13}C_{carb\text{-}coll}$ values coupled with higher $\delta^{15}N$ values may be generally indicative of marine protein consumption (Clementz *et al.* 2009, Kusaka *et al.* 2015). High $\Delta^{13}C_{carb\text{-}coll}$, low $\delta^{15}N$ values may be indicative that most of the dietary protein was plant-based (Kusaka *et al.* 2015). Based on this, values seen in some individuals at the Hospital detached cemetery and Friary may be indicative of marine protein consumption, while others at the Hospital may have had a largely plant based diet, although the range in means between subgroups is only 1.1‰, so conclusions may be limited.

Site Subgroup	*n*	Dentine Collagen		Enamel Carbonate	Enamel Carbonate-Dentine Collagen $\Delta^{13}C$ ($\Delta^{13}C_{carb\text{-}coll}$)					
		Mean $\delta^{15}N$ (‰) (VPDB)	*Mean* $\delta^{13}C$ (‰) (VPDB)	*Mean* $\delta^{13}C$ (‰) (VPDB)	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	40	11.4	-19.3	-12.5	6.8	0.5	6.9	7.6	5.2	2.4
All Saints	31	11.9	-19.5	-13.0	6.5	0.5	6.6	7.6	5.3	2.3
Hospital detached cemetery	55	12.1	-19.2	-12.8	6.4	0.6	6.5	7.7	5.1	2.6
Friary cemetery	16	12.1	-19.0	-12.8	6.2	0.4	6.3	6.7	5.4	1.3
St Bene't's	4	12.0	-19.1	-13.0	6.1	0.6	6.0	6.9	5.4	1.5
Hospital pit	1	12.1	-18.9	-13.1	5.8	NA	5.8	5.8	5.8	0.0
Clopton	12	11.4	-19.3	-13.4	6.0	0.7	5.8	7.1	4.6	2.5
Friary chapter house	4	12.8	-19.0	-13.4	5.7	0.5	5.7	6.2	5.1	1.1

Table 17: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$, enamel carbonate $\delta^{13}C$ and enamel carbonate-dentine collagen $\Delta^{13}C$ values for High/Late Medieval Cambridgeshire individuals, by site subgroup.

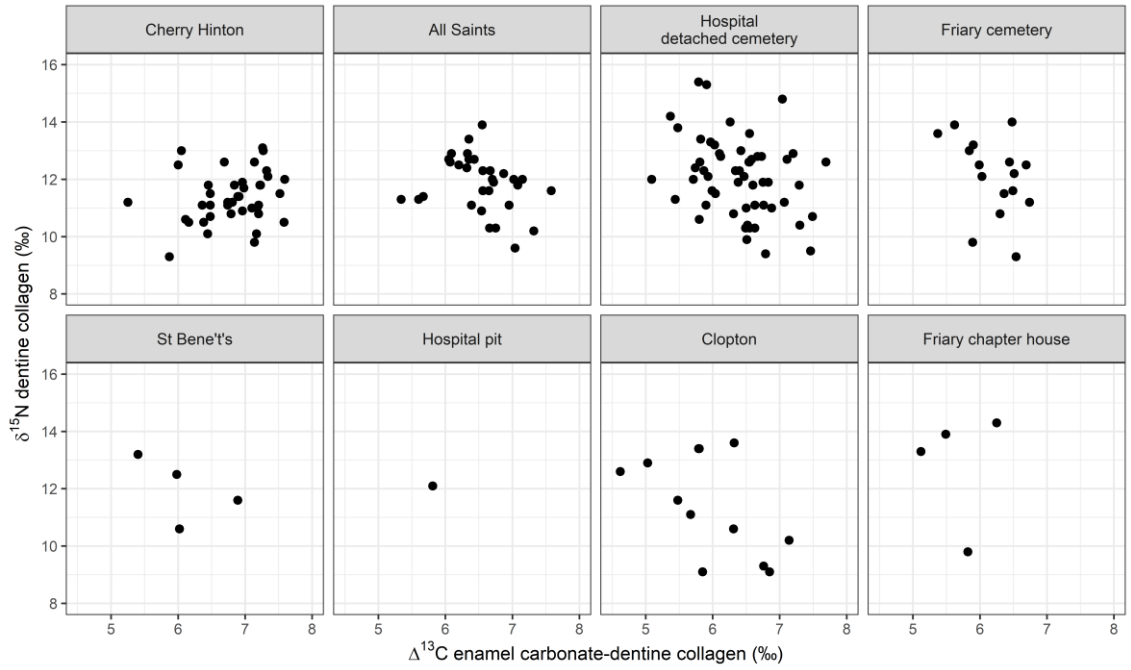


Figure 58: Scatterplots showing tooth enamel carbonate-dentine collagen $\Delta^{13}C$ and dentine $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals who were sampled for all three, by site subgroup

Kellner & Schoeninger (2007) have argued that using absolute $\Delta^{13}C_{bioapatite\text{-}coll}$ values is limited for understanding diet. Figure 59 shows a model proposed in Kellner & Schoeninger (2007) for characterising diets and identifying C_3 and C_4 contributions using bone collagen and bone apatite $\delta^{13}C$ values. The figure shows the modelled C_3 and C_4 protein lines and example data archaeological populations with various subsistence strategies.

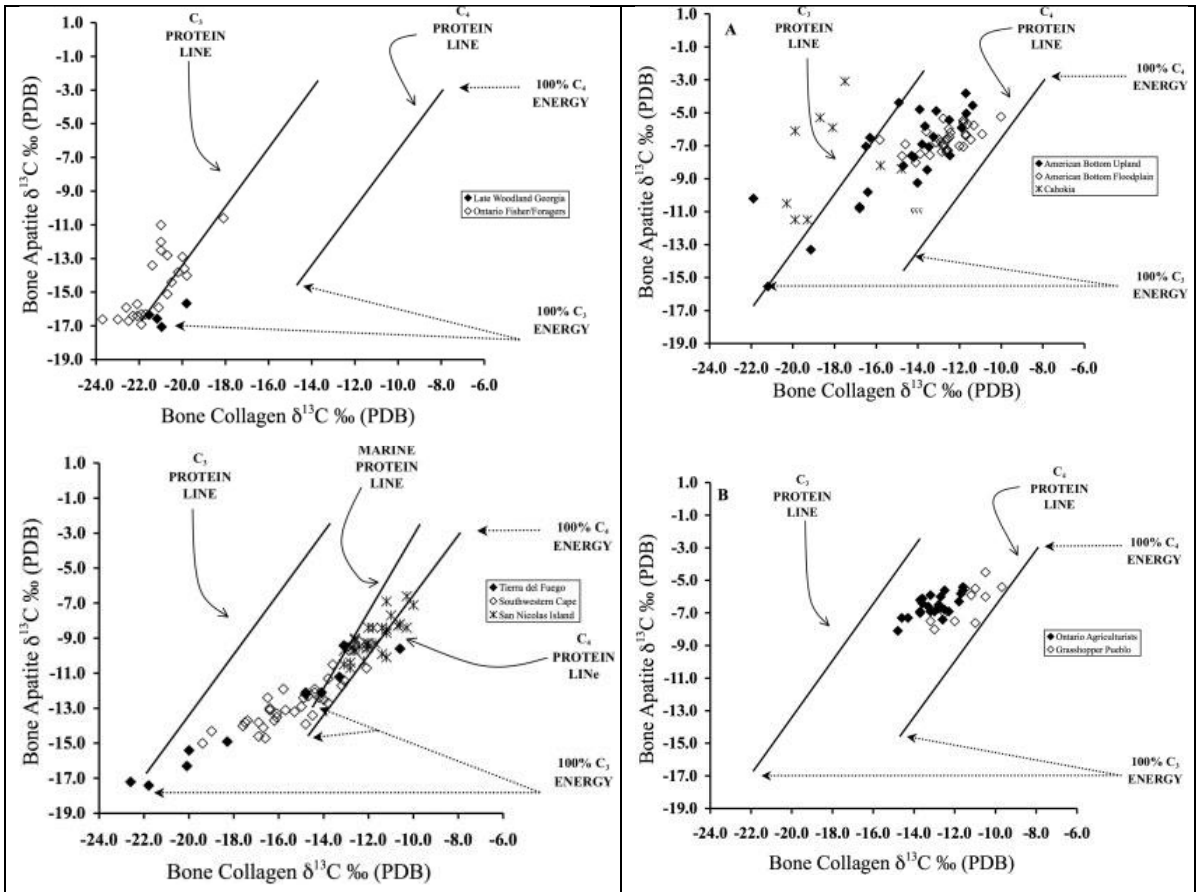


Figure 59: Example data from archaeological populations with modelled C_3 and C_4 protein lines from Kellner & Schoeninger (2007, pp. 1124–1125). Top left: archaeological populations lacking evidence for maize (C_4) agriculture, bottom left: population with marine protein and C_3 plants, top right: archaeological populations with access to C_4 foods and also fish, bottom right: one archaeological population eating fish, the other C_4 fed turkey.

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Following the model presented in Kellner & Schoeninger (2007). Figure 60 shows dentine collagen $\delta^{13}C$ and enamel carbonate $\delta^{13}C$ values from High/Late Medieval individuals from Cambridgeshire plotted against the modelled C_3 and C_4 protein lines, with the C_3 protein line on the left and C_4 protein line on the right. All the data is firmly clustered around the C_3 protein

line, with some drift in the data at the Hospital and Friary towards the C_4 line, although this is likely to be due to marine fish in their diet, rather than C_4 foods. Overall, in this study, considering carbonate carbon with collagen carbon does not elucidate much absolute information about diet but considering inter-subgroup variation in the values may still be interesting for charactering general differences.

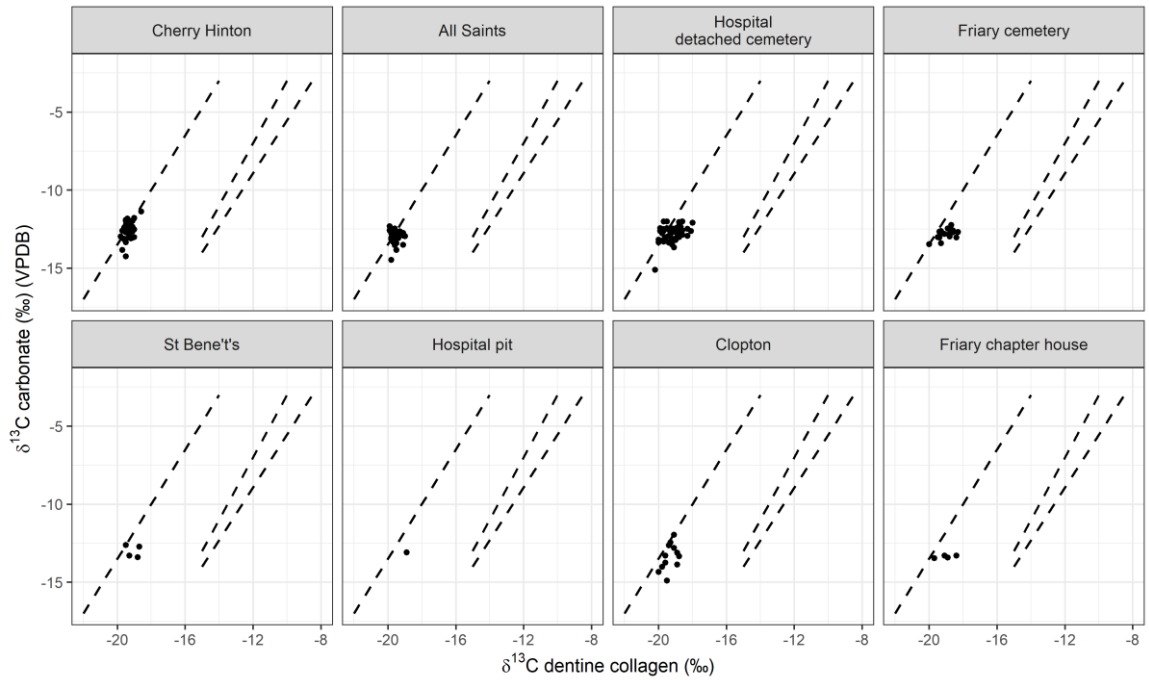


Figure 60: Scatterplots showing dentine collagen $\delta^{13}C$ and tooth enamel carbonate $\delta^{13}C$ values for all High/Late Medieval Cambridgeshire individuals, by subgroup. Dashed lines are modelled C_3 protein (left), marine protein (middle) and C_4 protein (right) lines following Kellner & Schoeninger (2007)

7.3 Overall Characterisation of High/Late Medieval Mobility

The enamel carbonate $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values plotted together show the narrow range for the $^{87}Sr/^{86}Sr$ and the extremely wide range for the $\delta^{18}O$ values (Figure 61). As discussed in Chapter 3, the median $^{87}Sr/^{86}Sr$ value estimated for central Cambridge is 0.7080-0.7090, but given the ambiguities in the data, a reasonable estimate for the 'localised' signature for Cambridge has been taken as 0.7080-0.7100 (based on Evans, Chenery, *et al.* 2018). This estimate is corroborated by the observed pattern in data (see marginal boxplot in Figure 61). The boxplot highlights some outliers, indicating that these individuals are unlikely to have spent their childhood in Cambridge.

Interpreting the $\delta^{18}O$ values is not as straightforward. As discussed in Chapter 3, the BGS Biosphere Isotope Domain map estimates the enamel carbonate $\delta^{18}O$ range for the East of Britain to be -5.28‰ to -4.06‰ and estimates the overall range for anywhere in Britain to be between -5.28‰ to -3.26‰ (Evans, Chenery, *et al.* 2018). A substantial proportion of the Cambridgeshire individuals have lower values than these estimates (Figure 61). Lightfoot & O'Connell (2016) estimate the normal range of human $\delta^{18}O$ values to be 3.0‰ or larger in archaeological populations. The overall range for the combined High/Late Medieval enamel carbonate $\delta^{18}O$ is 5.6‰, well above the 'normal range' of 3.0‰. The boxplot identifies only one outlier beyond 1.5IQR. In short, the $\delta^{18}O$ data has an unusually large range, however, given the context, the small number of outliers and the narrow range of $^{87}Sr/^{86}Sr$ values, it is unlikely that such a substantial portion of the individuals spent their childhoods outside of the East of Britain, or even outside of Britain altogether, as is suggested when using ranges from the BGS map. Due to the ambiguities in the data, for this study, only individuals identified as outliers using the 1.5IQR method will be considered to be 'non-local'.

Overall, the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values indicate that most of the High/Late Medieval population could be interpreted as 'local', with values that indicate they could have spent their childhoods near where they were buried (Bentley 2006, Pollard 2011). Only a few have $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values that indicate they did not spend their childhoods in the local area. This shows that a certain degree of mobility can be detected in the data, despite the reservations regarding the potential homogeneity of the data discussed in Chapter 3. Further interpretations of mobility

and migration in High/Late Medieval Cambridge are discussed in more detail in Chapter 9, Section 9.3.

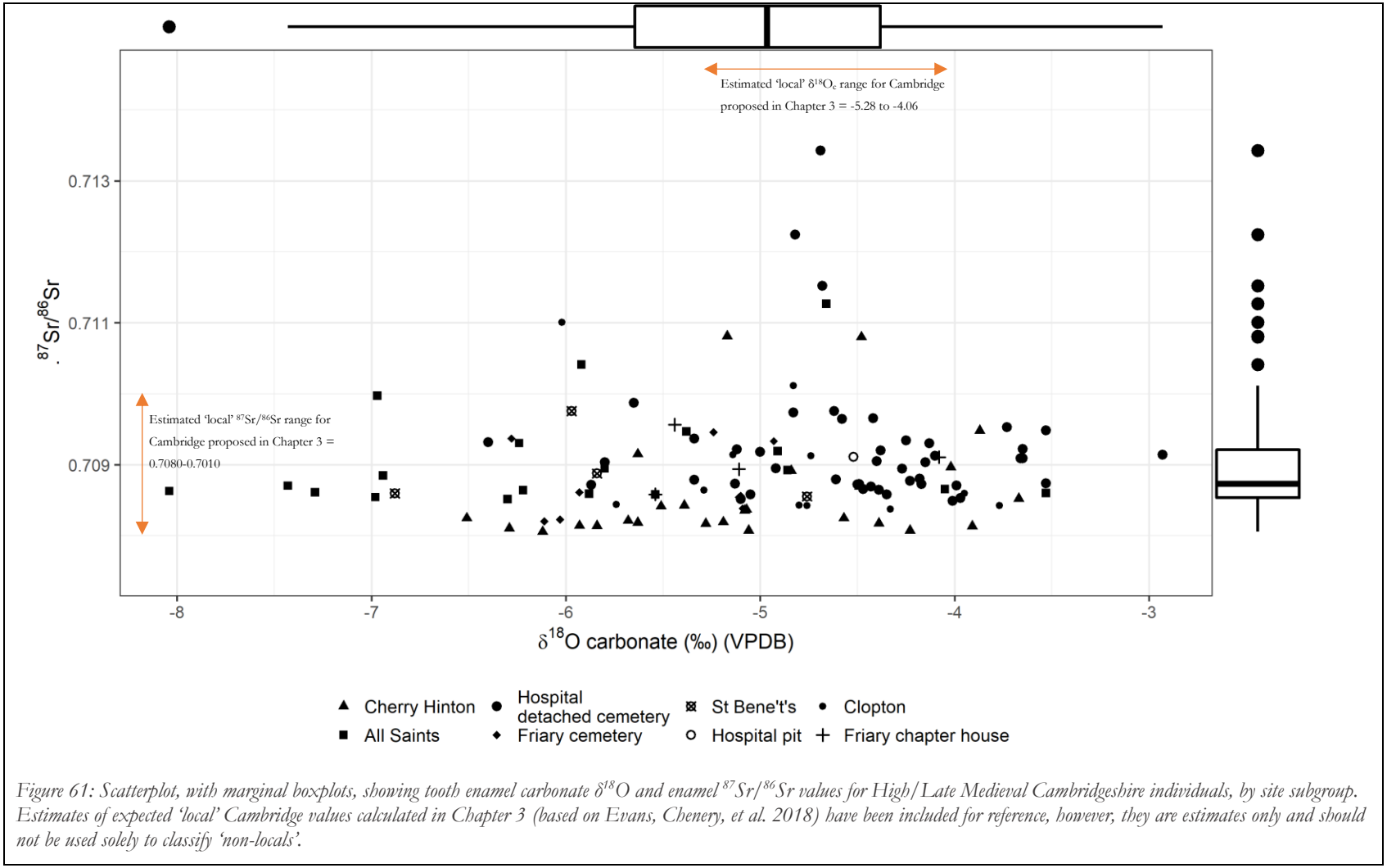


Figure 61: Scatterplot, with marginal boxplots, showing tooth enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals, by site subgroup. Estimates of expected 'local' Cambridge values calculated in Chapter 3 (based on Evans, Chenery, et al. 2018) have been included for reference, however, they are estimates only and should not be used solely to classify 'non-locals'.

7.4 High/Late Medieval Human Isotope Results by Site Subgroup

To see if there are any meaningful differences across various cemetery groups, this section investigates the isotope data by site subgroup. This was deemed a more appropriate division than by site only, as it separates the groups by broad burial contexts, avoiding conflation of those that were not from a similar time period, or burial population.

7.4.1 Results: Site Subgroup

There are differences in the mean, median, range and distribution of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values by site subgroup, but $^{87}Sr/^{86}Sr$ values are very similar (Table 18 to Table 22, Figure 62 to Figure 65).

The distribution of dentine and rib $\delta^{13}C$ and $\delta^{15}N$ values show that the majority of individuals at Cherry Hinton are consistently below the population mean, while those at the Friary sites are consistently above and those at the Hospital consistently have the largest range (Figure 62). Comparing the mean, standard deviation (SD) and scatter of the $\delta^{13}C$ and $\delta^{15}N$ data from each site subgroup shows that some subgroups are quite distinct and that the differences are more pronounced in the rib collagen data (Figure 66). The values from the Friary subgroups stand out, particularly the higher rib collagen $\delta^{15}N$ values at the Friary cemetery (Figure 66). For enamel carbonate $\delta^{13}C$ values, the pattern is almost reversed, with Clopton and the Friary chapter house having the lowest mean value at -13.4‰ and Cherry Hinton having the highest mean value at -12.5‰ (Table 20, Figure 64). The Hospital detached cemetery has the widest carbonate $\delta^{13}C$ range, but it is clear from Figure 64 that this is driven by one extreme outlier and that Clopton has the widest general spread in data.

There is a wide range in the enamel carbonate $\delta^{18}O$ values for all site subgroups (Table 21, Figure 64). St Bene't's has the lowest mean value at -5.9‰, and the Hospital pit has the highest, at -4.5‰, although both these sites have small sample numbers. All Saints has the largest range (4.5‰), as can be seen in Figure 64. No sites exhibit extreme $\delta^{18}O$ outliers. It is interesting that All Saints has a much larger range than say, the Hospital, given that they are in relative proximity and should represent partially overlapping social groups (Cessford in Robb n.d.,

Cessford 2015). If the values are reflective of the climate where a person spent their childhood (and therefore potentially their geographical origins) (Pederzani and Britton 2019), this could indicate a wider catchment area of people who end up buried at All Saints, however this will be discussed further in Chapter 9.

The majority of the enamel $^{87}Sr/^{86}Sr$ values are constrained to a relatively small range - the maximum range in median values is only 0.0009 across all site subgroups (Table 22). Cherry Hinton has the lowest median value at 0.7082. The majority of $^{87}Sr/^{86}Sr$ values in each subgroup fall within the estimate for the 'local' signature for Cambridge of 0.7080-0.7100, but several outliers are present, meaning a small minority of those sampled are unlikely to have spent their childhood in Cambridge (Figure 65). These are from a variety of site subgroups and are discussed further in Section 7.4.2 below.

Site Subgroup	*n*	Dentine $\delta^{13}C$ (‰) (VPDB)						Dentine $\delta^{15}N$ (‰) (AIR)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	40	-19.3	0.2	-19.4	-19.8	-18.6	1.2	11.4	0.9	11.2	9.3	13.1	3.8
All Saints	31	-19.5	0.3	-19.6	-19.9	-19.0	0.9	11.9	1.0	12.0	9.6	13.9	4.3
Hospital detached cemetery	55	-19.2	0.5	-19.2	-20.2	-18.0	2.2	12.1	1.4	12.1	9.4	15.4	6.0
Friary cemetery	16	-19.0	0.5	-19.0	-20.0	-18.3	1.7	12.1	1.4	12.3	9.3	14.0	4.7
St Bene't's	4	-19.1	0.4	-19.1	-19.5	-18.7	0.8	12.0	1.1	12.1	10.6	13.2	2.6
Hospital pit	1	-18.9	-	-18.9	-18.9	-18.9	-	12.1	-	12.1	12.1	12.1	-
Clopton	12	-19.3	0.4	-19.4	-20.0	-18.8	1.2	11.4	1.8	11.3	9.1	13.6	4.5
Friary chapter house	4	-19.0	0.5	-19.0	-19.7	-18.4	1.3	12.8	2.1	13.6	9.8	14.3	4.5
TOTAL	**163**												

Table 18: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by site subgroup.

Site Subgroup		n	Rib δ13C (‰) (VPDB)						Rib δ15N (‰) (AIR)					
			Mean	SD	Median	Min	Max	Range	Mean	SD	Median	Min	Max	Range
Cherry Hinton	**ALL**	47	-19.6	0.2	-19.6	-19.9	-19.1	0.8	11.6	0.9	11.7	9.4	13.0	3.6
	Adult	44	-19.6	0.2	-19.6	-19.9	-19.1	0.8	11.6	1.0	11.8	9.4	13.0	3.6
	Non-Adult	3	-19.7	0.2	-19.8	-19.8	-19.5	0.3	11.4	0.0	11.4	11.4	11.4	0.0
All Saints	**ALL**	43	-19.4	0.4	-19.4	-20.2	-18.4	1.8	12.4	0.7	12.4	11.1	14.3	3.2
	Adult	40	-19.4	0.4	-19.4	-20.2	-18.4	1.8	12.4	0.7	12.4	11.1	14.3	3.2
	Non-Adult	3	-19.6	0.2	-19.6	-19.8	-19.5	0.3	12.5	0.5	12.4	12.0	13.0	1.0
Hospital detached cemetery	**ALL**	149	-19.0	0.4	-19.0	-19.9	-17.7	2.2	12.3	1.2	12.4	8.3	15.2	6.9
	Adult	114	-19.0	0.4	-19.0	-19.8	-17.7	2.1	12.5	1.1	12.5	9.7	15.2	5.5
	Non-Adult	35	-19.1	0.4	-19.1	-19.9	-18.3	1.6	11.9	1.3	12.0	8.3	14.1	5.8
Friary cemetery	**ALL**	23	-18.4	0.4	-18.4	-19.7	-17.5	2.2	13.8	0.9	14.1	10.6	14.9	4.3
	Adult	19	-18.3	0.3	-18.4	-18.9	-17.5	1.4	14.0	0.5	14.1	13.2	14.9	1.7
	Non-Adult	4	-18.9	0.6	-18.9	-19.7	-18.3	1.4	12.9	1.6	13.4	10.6	14.2	3.6
Hospital pit	**ALL**	4	-19.5	0.2	-19.5	-19.6	-19.3	0.3	11.3	1.8	11.4	9.2	13.2	4.0
	Adult	2	-19.4	0.1	-19.4	-19.4	-19.3	0.1	12.7	0.7	12.7	12.2	13.2	1.0
	Non-Adult	2	-19.6	0.0	-19.6	-19.6	-19.6	0.0	9.9	1.0	9.9	9.2	10.6	1.4
Clopton	**ALL**	13	-19.5	0.3	-19.6	-20.0	-19.0	1.0	11.5	1.7	12.2	8.2	13.2	5.0
	Non-adult	12	-19.5	0.3	-19.6	-20.0	-19.0	1.0	11.4	1.7	12.2	8.2	13.2	5.0
	Unk	1	-19.6	-	-19.6	-19.6	-19.6	-	12.8	-	12.8	12.8	12.8	-
Friary chapter house	**ALL**	5	-19.1	0.4	-19.1	-19.7	-18.5	1.2	13.6	0.3	13.6	13.3	14.0	0.7
	Adult	4	-18.9	0.3	-19.1	-19.1	-18.5	0.6	13.7	0.2	13.7	13.5	14.0	0.5
	Non-Adult	1	-19.7	-	-19.7	-19.7	-19.7	-	13.3	-	13.3	13.3	13.3	-
TOTAL	**ALL**	**284**												
	Adult	**223**												
	Non-Adult	**57**												

Table 19: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by site subgroup. Where non-adults were also sampled, the data is broken down by adult/non-adult.

Site Subgroup	*n*	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	40	-12.5	0.6	-12.5	-14.2	-11.4	2.8
All Saints	34	-13.0	0.5	-12.9	-14.5	-12.0	2.5
Hospital detached cemetery	84	-12.7	0.5	-12.7	-15.1	-11.7	3.4
Friary cemetery	17	-12.8	0.3	-12.8	-13.5	-12.2	1.3
St Bene't's	4	-13.0	0.4	-13.0	-13.4	-12.6	0.8
Hospital pit	1	-13.1	-	-13.1	-13.1	-13.1	-
Clopton	12	-13.4	0.8	-13.3	-14.9	-12.0	2.9
Friary chapter house	4	-13.4	0.1	-13.3	-13.4	-13.3	0.1
TOTAL	**196**						

Table 20: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values, for High/Late Medieval Cambridgeshire individuals, by site subgroup.

Site Subgroup	*n*	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						*Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)*					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	40	-5.0	0.7	-5.1	-6.5	-3.7	2.8	16.9	0.8	16.8	15.3	18.3	3.0
All Saints	34	-5.6	1.1	-5.5	-8.0	-3.5	4.5	16.2	1.2	16.4	13.7	18.5	4.8
Hospital detached cemetery	84	-4.6	0.8	-4.5	-6.4	-2.4	4.0	17.4	0.9	17.4	15.4	19.6	4.2
Friary cemetery	17	-5.6	0.6	-5.5	-6.5	-4.2	2.3	16.3	0.7	16.3	15.3	17.7	2.4
St Bene't's	4	-5.9	0.9	-5.9	-6.9	-4.8	2.1	16.0	0.9	15.9	14.9	17.2	2.3
Hospital pit	1	-4.5	-	-4.5	-4.5	-4.5	-	17.4	-	17.4	17.4	17.4	-
Clopton	12	-4.9	0.7	-4.8	-6.0	-3.8	2.2	17.0	0.7	17.1	15.8	18.2	2.4
Friary chapter house	4	-5.0	0.7	-5.3	-5.5	-4.1	1.4	16.9	0.7	16.6	16.3	17.9	1.6
TOTAL	**196**												

Table 21: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$ using (Chenery *et al.* 2012)*) and $\delta^{13}C$ values, for High/Late Medieval Cambridgeshire individuals, by site subgroup.*

Site Subgroup	*n*	Enamel $^{87}Sr/^{86}Sr$						Sr ppm	
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Cherry Hinton	26	0.7086	0.0007	0.7082	0.7081	0.7108	0.0027	131	38
All Saints	19	0.7091	0.0007	0.7087	0.7085	0.7113	0.0028	143	38
Hospital detached cemetery	46	0.7092	0.0009	0.7090	0.7085	0.7134	0.0049	121	35
Friary cemetery	12	0.7087	0.0004	0.7086	0.7082	0.7095	0.0013	113	50
St Bene't's	4	0.7089	0.0006	0.7087	0.7086	0.7098	0.0012	110	40
Hospital pit	1	0.7091	-	0.7091	0.7091	0.7091	0.0000	107	-
Clopton	11	0.7090	0.0009	0.7086	0.7084	0.7110	0.0026	145	63
Friary chapter house	4	0.7090	0.0004	0.7090	0.7086	0.7096	0.0010	86	14
TOTAL	**123**								

Table 22: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values and Sr ppm, for High/Late Medieval Cambridgeshire individuals, by site subgroup

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

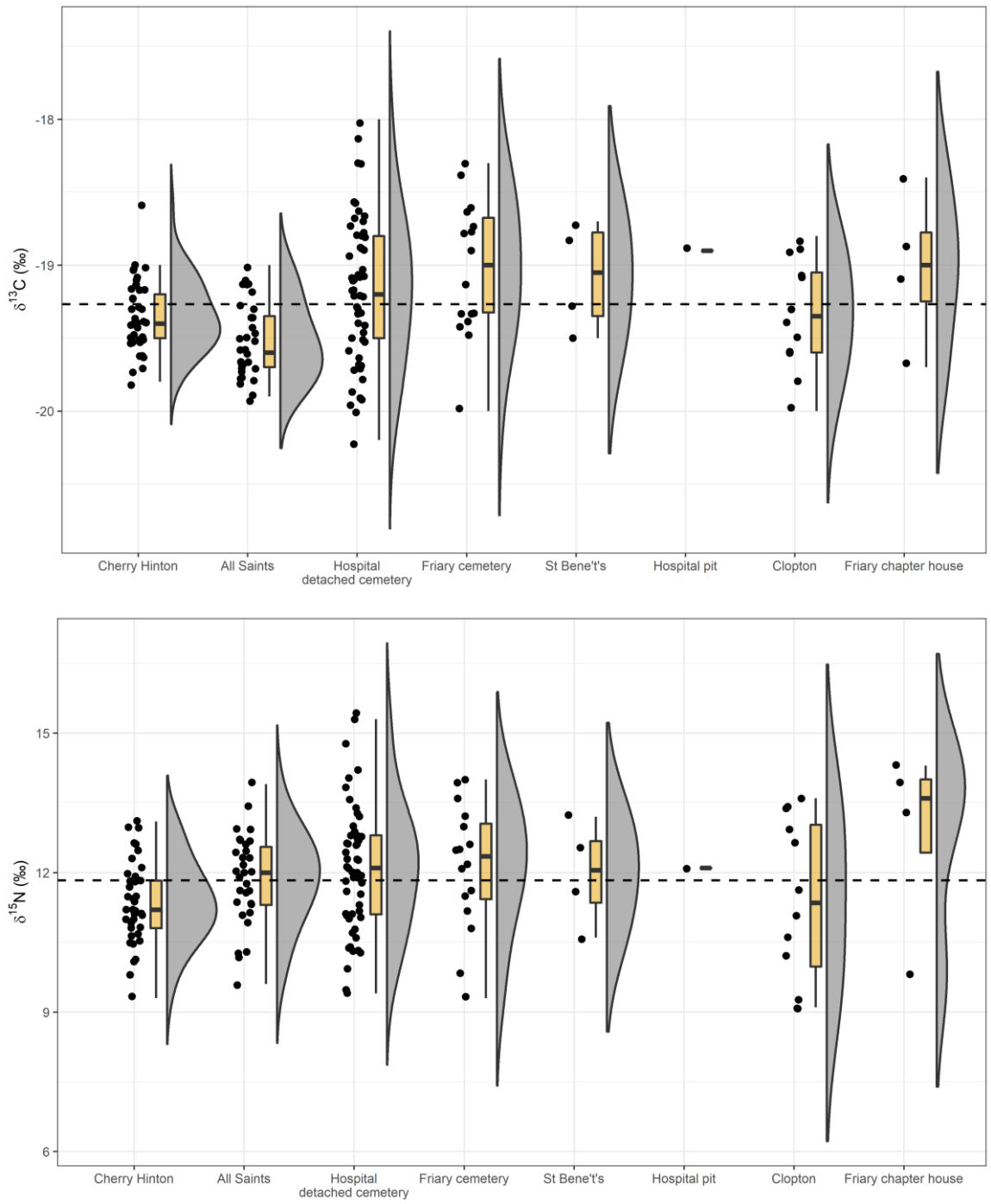


Figure 62: Raincloud plots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

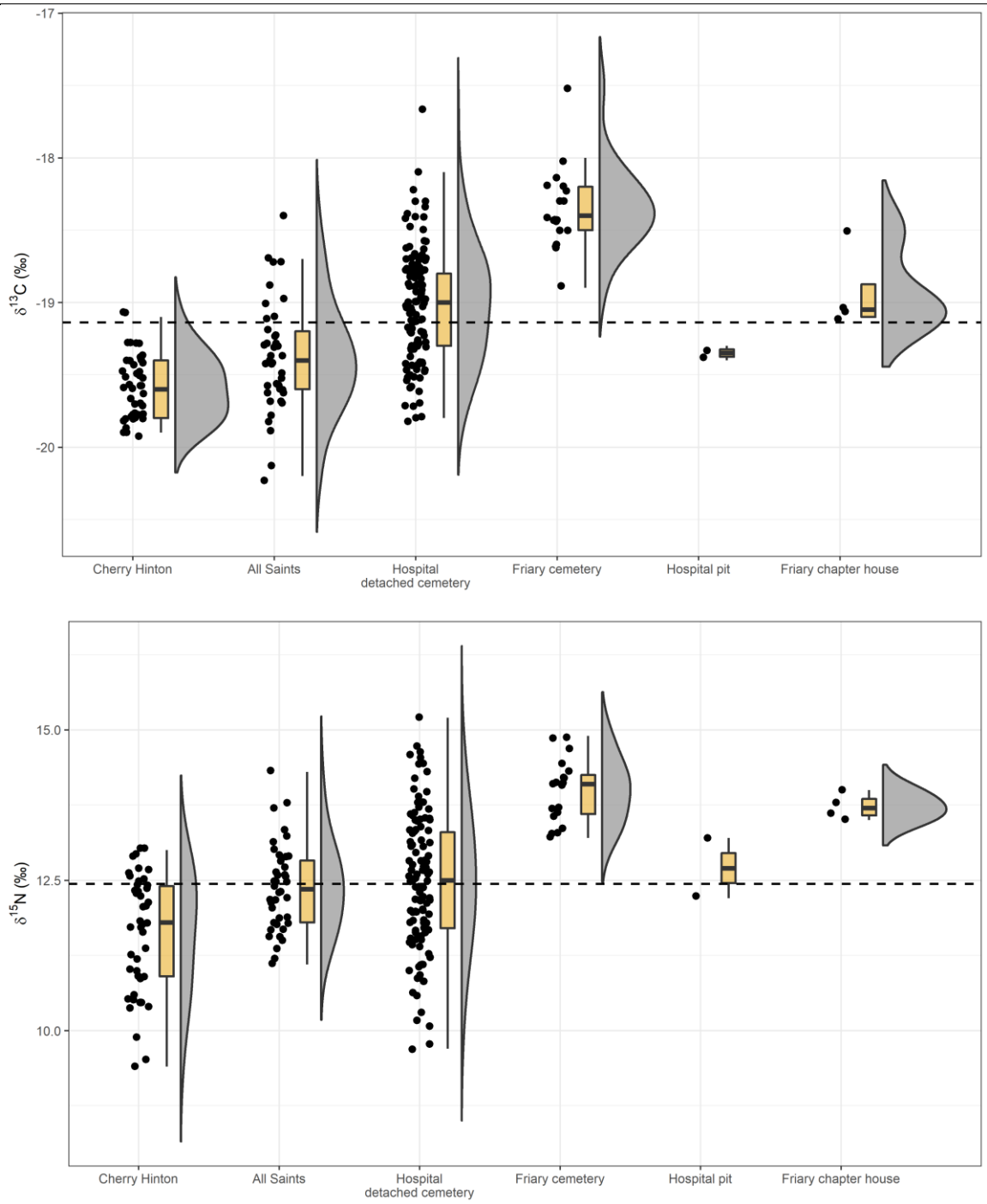


Figure 63: Raincloud plots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all adult High/Late Medieval Cambridgeshire individuals, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

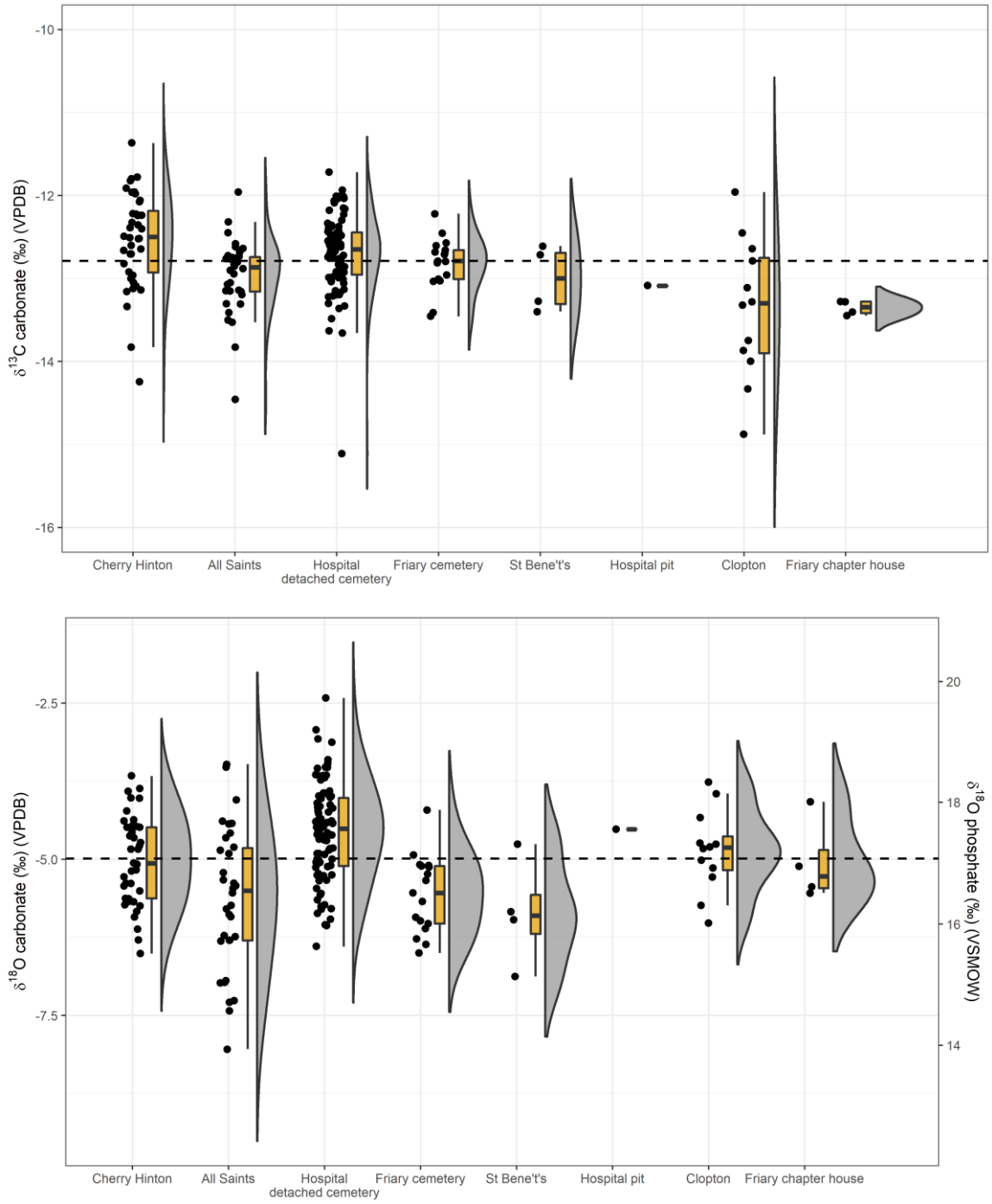


Figure 64: Raincloud plots showing tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all High/Late Medieval Cambridgeshire individuals, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Enamel $^{87}Sr/^{86}Sr$

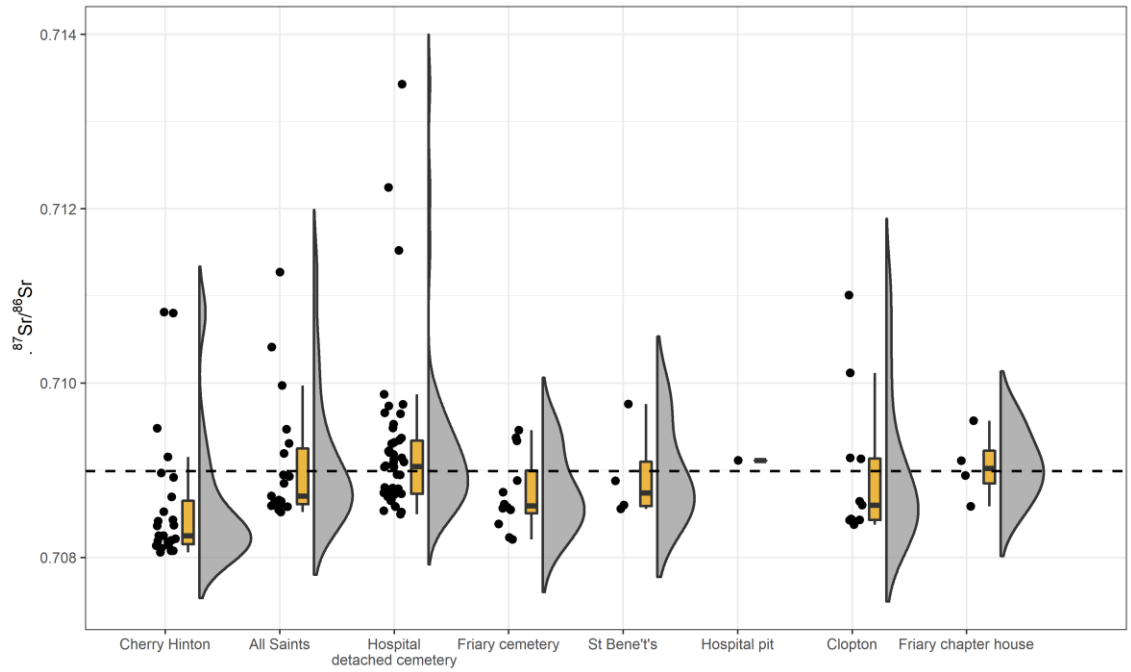


Figure 65: Raincloud plot showing tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in the plot

Dentine and Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

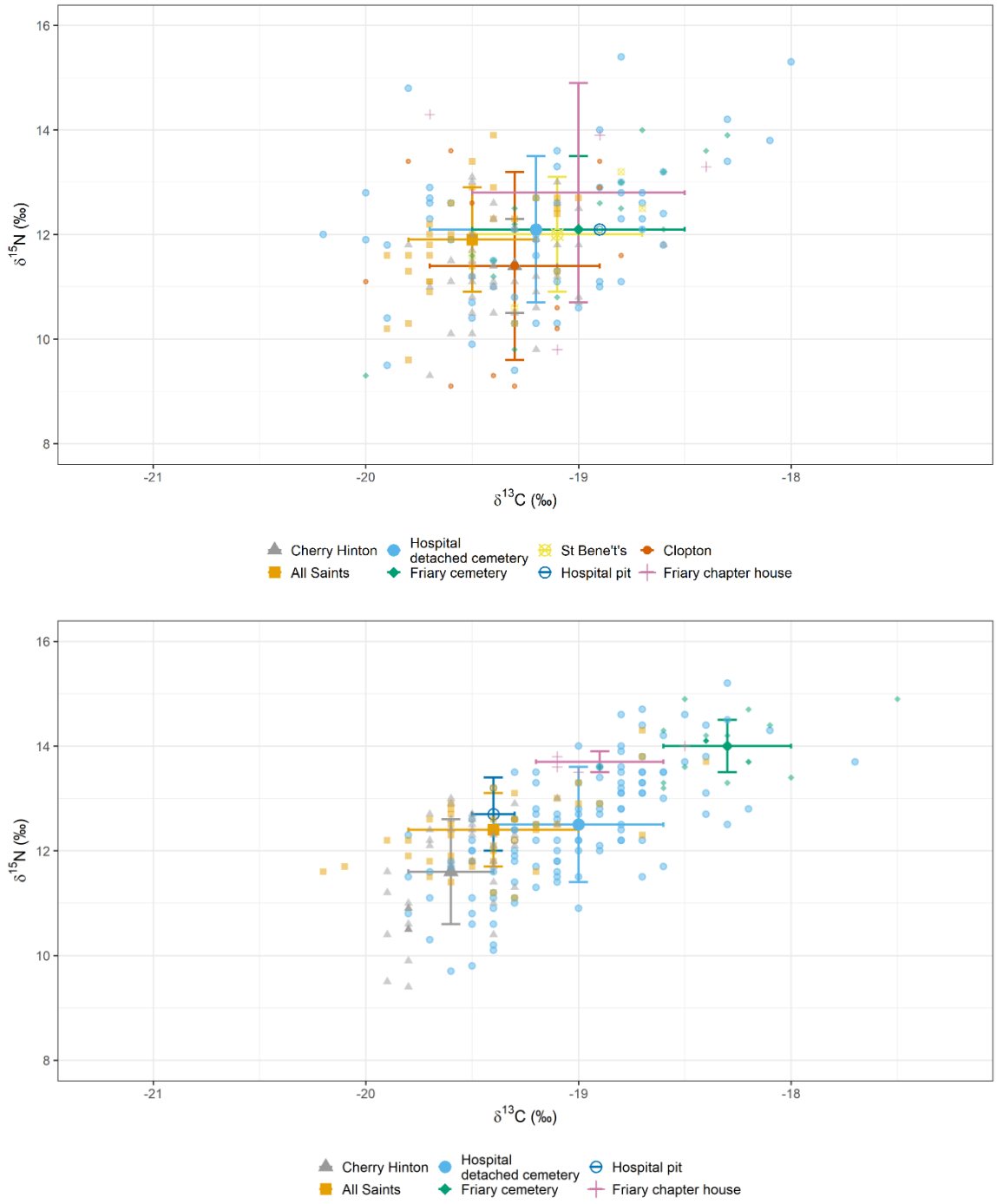


Figure 66: Scatterplots showing mean and individual dentine and adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals analysed, by site subgroup. Error bars indicate 1 SD from the mean.

7.4.2 Outliers: Site Subgroup

Almost all the site subgroups have outliers for at least one isotope (Figure 62 to Figure 65, Table 23). There are more outliers for $\delta^{13}C$ values than $\delta^{15}N$. There is only one dentine collagen $\delta^{13}C$ outlier but four rib collagen $\delta^{13}C$ outliers - PSN 703 from All Saints, PSN 79 from the Hospital detached cemetery, PSN 509 from the Friary Cemetery and PSN 516 from the Friary chapter house. All of these individuals are males and are outliers with higher $\delta^{13}C$ values than the other individuals in their subgroups. Cherry Hinton, All Saints and the Hospital detached cemetery all have distinct enamel carbonate $\delta^{13}C$ outliers with lower values, which is likely to be why the distribution and tests of normality for enamel carbonate $\delta^{13}C$ are abnormal. These individuals are all adults, a mix of both sexes and span a wide date range. There are two dentine collagen $\delta^{15}N$ outliers – PSN 231 from the Hospital detached cemetery and PSN 507 from the Friary cemetery but there are no rib collagen $\delta^{15}N$ outliers by subgroup.

There are no enamel carbonate $\delta^{18}O$ outliers by site subgroup but there are nine outliers with high $^{87}Sr/^{86}Sr$ values, which are not consistent with values expected for Cambridge (Evans, Chenery, *et al.* 2018) (Table 23). These individuals are from four of the High/Late Medieval sites and span over 500 years, indicating the infrequency of outliers and their presence across subgroups. They are a mixture of males and females and are a mixture of ages, although four out of the nine (44%) are classed as Young Middle Adults (26-35yr). Two of the individuals – PSNs 930 and 746 are also outliers for enamel carbonate $\delta^{13}C$, adding the possibility that these individuals spent their childhood in a different place to the other individuals in their site subgroup. Incidentally, when the enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values were combined previously in Figure 61, eight of the nine outliers by site subgroup are highlighted as overall outliers for $^{87}Sr/^{86}Sr$ (PSN 907 is not an overall outlier) and one individual is highlighted as an overall outlier for enamel carbonate $\delta^{18}O$ – PSN 728, a High Medieval female from All Saints.

Site Subgroup	*PSN*	*Est. Death Date*	*Est. median death date*	*Sex*	*Age (yr)*	Dentine Collagen		Rib Collagen		Enamel Carb		Enamel
						$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{18}O$	$^{87}Sr/^{86}Sr$
Cherry Hinton	907	High Medieval c.940-1170	1055	F	46-59	-19.7	12.4	-19.5	11.7	-12.5	-3.9	**0.7095**
	912	High Medieval c.1000-1170	1085	F	46-59	**-18.6**	11.8	-19.8	9.4	-11.4	-4.6	-
	918	High Medieval c.940-1100	1020	M	26-35	-19.8	10.9	-19.3	10.5	-12.9	-4.5	**0.7108**
	930	High Medieval c.940-1170	1055	F	36-45	-19.8	9.9	-19.7	9.3	**-13.8**	-5.2	**0.7108**
	949	High Medieval c.940-1170	1055	M	45+	-19.6	11.7	-19.5	11.2	**-14.3**	-4.5	-
All Saints	703	High Medieval c.1050-1250	1050	M	46-59	-19.1	12.5	**-18.4**	13.7	-12.9	-3.5	0.7086
	741	High Medieval c.1050-1100	1075	F	36-45	-	-	-19.5	11.4	**-13.8**	-7.3	-
	746	High Medieval c.1050-1250	1150	M	36-45	-	-	-19.8	11.3	**-14.5**	-4.7	**0.7113**
	781	High Medieval c.940-1365	1152.5	F	26-35	-	-	-19.4	12.9	-13.1	-5.9	**0.7104**
Hospital detached cemetery	66	Late Medieval c.1270-1380	1325	M	18-25	-19.4	11.2	-19.9	9.5	-12.4	-4.7	**0.7134**
	79	Late Medieval c.1204-1330	1204	M	18-25	-	-	**-17.7**	13.7	-	-	-
	99	Late Medieval c.1330-1400	1365	M	26-35	-19.2	11.3	-18.9	11.1	-13.0	-4.7	**0.7115**
	231	Late Medieval c.1240-1350	1295	M	46-59	-18.8	**15.4**	-18.6	14.2	-13.0	-4.7	-
	332	Late Medieval c.1264-1308	1286	F	18-25	-18.9	12.9	-19.7	12.3	-13.3	-4.8	**0.7122**
	339	Late Medieval c.1370-1511	1440	F	25-35	-19.7	11.6	-20.2	12.0	**-15.1**	-5.3	0.7094
Friary cemetery	507	Late Medieval c.1475-1536	1505.5	M	7-12	-19.1	**9.8**	-	-	-13.3	-5.5	0.7086
	509	Late Medieval c.1290-1349	1290	M	36-45	-18.6	13.2	**-17.5**	14.9	-12.7	-5.3	-
Clopton	1238	Late Medieval c.1200-1561	1380.5	M	26-35	-	-	-19.6	9.1	-13.8	-6.0	**0.7110**
Friary chapter house	516	Late Medieval c.1360-1500	1360	M	18-25	-18.4	13.3	**-18.5**	14.0	-12.3	-5.1	0.7089

Table 23: Summary information and isotope values for subgroup outliers from the High/Late Medieval site subgroups (see section 5.1.1 for explanations of categorisations e.g. death date, sex, age). The value which they are outliers for is highlighted in grey

7.4.3 Statistical Testing: Site Subgroup

Comparisons by site subgroup show that dentine $\delta^{13}C$, rib $\delta^{13}C$ and $\delta^{15}N$ and enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ are not taken from populations with the same distribution but the null hypothesis could not be rejected for dentine collagen $\delta^{15}N$ (Kruskal-Wallis tests: dentine $\delta^{13}C$: p=<0.001, rib $\delta^{13}C$: p=<0.001, enamel carbonate $\delta^{13}C$: p=<0.001, dentine $\delta^{15}N$: p=0.054, rib $\delta^{15}N$: p=<0.001, enamel carbonate $\delta^{18}O$: p=<0.001). Dunn's post-hoc tests with Bonferroni adjustment show which site subgroups differ in their isotope value distributions (see Table 24 for results where *p-adj* = <0.05, see Table XLVI in Appendix VI for full results). The results confirm that differences in isotope values are present across site subgroups and broadly show a difference between the parish sites and the Friary/Hospital sites.

					Dunn's Test (with Bonferroni adj)			
	Group 1	***Group 2***	***n1***	***n2***	*statistic*	*p*	*p.adj*	*p.adj.signif*
$\delta^{13}C$ Dent Coll	All Saints	Hospital detached cemetery	31	55	3.864574	<0.001	0.002337	**
	All Saints	Friary cemetery	31	16	3.938277	<0.001	0.001723	**
$\delta^{13}C$ Adult Rib Coll	Cherry Hinton	Hospital detached cemetery	44	114	7.313601	<0.001	<0.001	****
	Cherry Hinton	Friary cemetery	44	19	8.847287	<0.001	<0.001	****
	Cherry Hinton	Friary chapter house	44	4	2.967665	0.003001	0.030007	*
	All Saints	Hospital detached cemetery	40	114	4.211657	<0.001	<0.001	***
	All Saints	Friary cemetery	40	19	6.83602	<0.001	<0.001	****
	Hospital detached cemetery	Friary cemetery	114	19	4.563004	<0.001	<0.001	****
$\delta^{13}C$ Enamel Carb	Cherry Hinton	All Saints	40	34	-3.92673	<0.001	0.001808	**
	Cherry Hinton	Clopton	40	12	-3.72288	<0.001	0.004136	**
	Cherry Hinton	Friary chapter house	40	4	-3.40796	<0.001	0.013745	*
$\delta^{15}N$ Adult Rib Coll	Cherry Hinton	Hospital detached cemetery	44	114	3.94414	<0.001	<0.001	***
	Cherry Hinton	Friary cemetery	44	19	7.28468	<0.001	<0.001	****
	Cherry Hinton	Friary chapter house	44	4	3.625238	<0.001	0.002887	**
	All Saints	Friary cemetery	40	19	5.046135	<0.001	<0.001	****
	Hospital detached cemetery	Friary cemetery	114	19	5.245223	<0.001	<0.001	****
	All Saints	Hospital detached cemetery	34	83	5.0215	<0.001	<0.001	****

$\delta^{18}O$ Enamel Carb	Hospital detached cemetery	Friary cemetery	83	17	-4.35331	<0.001	<0.001	***

Table 24: Results of Dunn's post-hoc test comparing $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values for High/Late Medieval Cambridgeshire individuals analysed, by site subgroup (excluding Hospital pit).Only showing results where the adjusted p-value = <0.05, see Table XLVI in Appendix VI for full results.

7.4.4 Summary: Site Subgroup

This section has demonstrated isotopic differences between site subgroups, which could indicate that some of these cemetery populations were at least partially distinct from other nearby cemetery groups. To see differences in groups which are spatially and temporally close is exciting for isotope research and shows the dataset has great potential to address questions of social difference.

The statistics and exploratory plots show there are meaningful differences in $\delta^{13}C$ and $\delta^{15}N$ values between the different subgroups. Statistical testing shows that there are differences between the dentine, rib and enamel carbonate $\delta^{13}C$ and rib $\delta^{15}N$ values for several site subgroups, indicating that many are isotopically distinct. Some sites appear to have a very characteristic isotopic profile, with the Friary subgroups having consistently higher $\delta^{15}N$ values and the Hospital detached cemetery having a much larger isotope range. It is likely that varying access to marine protein is driving a lot of the difference in $\delta^{13}C$ and $\delta^{15}N$ values, with the high $\delta^{13}C$ and $\delta^{15}N$ values at the Friary being indicative of more regular marine protein consumption than other groups (Minagawa and Wada 1984, Schoeninger and DeNiro 1984, Müldner and Richards 2007b). Urban/rural differences may also be present: the 'rural' parish sites of Cherry Hinton and Clopton have the lowest mean dentine and rib collagen $\delta^{15}N$ values and post-hoc tests show that Cherry Hinton is distinct in $\delta^{15}N$ to the Hospital and the Friary subgroups. Low $\delta^{15}N$ values at these sites could attest to lower consumption of animal proteins than those in the urban sites (Minagawa and Wada 1984, O'Connell and Hedges 1999), although it should also be noted that Cherry Hinton is also much earlier in date.

The $^{87}Sr/^{86}Sr$ values are very similar across all site subgroups. Nine $^{87}Sr/^{86}Sr$ outliers were identified but these are from various subgroups, indicating that no one site was more isotopically diverse than another. The $\delta^{18}O$ values appear to show more variation by subgroup, with All Saints and the Hospital detached cemetery showing ranges in $\delta^{18}O$ values well over the expected level of variation (Lightfoot & O'Connell 2016). These two sites are also flagged by

statistical testing as having different sample distributions. However, there are no enamel carbonate $\delta^{18}O$ outliers when the data is considered by site subgroup and only one when the data is pooled. Overall, the $\delta^{18}O$ values are difficult to interpret, but there does appear to be some difference by site subgroup, although not enough to identify any 'non-locals' at any one site. As outlined in Chapter 3, possible causes of variation in $\delta^{18}O$ values include variable evaporation, (potentially indicating variable exploitation of water sources), variable preparation of food and water, and climate (Pederzani and Britton 2019). Possible explanations for the variation in the Cambridgeshire data will be explored further in Chapter 9, Section 9.3. .

7.5 High/Late Medieval Human Isotope Results by Sex

This section investigates adult dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$, enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values by sex only and by sex and site subgroup, to see if there are any meaningful differences in isotope values between females and males which could imply differential access to foods, or differential patterns of mobility and migration. Despite some non-adults having sex estimates based on aDNA results, for consistency, only adults (>18yr) who had been reliably sexed to either a male or female category are considered in this section.

7.5.1 Results: Sex

The summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values, enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ values, and enamel $^{87}Sr/^{86}Sr$ values show very little overall difference between High/Late Medieval females and males (Table 25 to Table 29). Only adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ values show some differences between females and males, with the mean $\delta^{13}C$ value being -19.3‰ for females and -19.0‰ for males and the mean $\delta^{15}N$ value being 12.2‰ for females and 12.6‰ for males (Table 26).

While the mean and median values are generally similar, there are some differences in the range and distribution of the data. For dentine collagen, the $\delta^{15}N$ range is much larger in males (6.3‰) than females (4.6‰) (Table 25, Figure 67). Figure 68 highlights the much more elongated distribution in the data in the males, with a greater number of individuals with high $\delta^{15}N$ values. For rib collagen, there is a much larger range in male values for both $\delta^{13}C$ and $\delta^{15}N$ (Table 26, Figure 69), and again, males have a more elongated distribution in their data (Figure 70). On further analysis, it is clear a lot of the trends in both the rib and dentine data are being driven by small number of males from the Friary and Hospital cemeteries with high $\delta^{13}C$ and $\delta^{15}N$ values, however, it is interesting that the inner 'bag' in Figure 68 is still similar for males and females but quite different in Figure 70, indicating that sex-based differences are more pronounced in rib than dentine data.

While the enamel carbonate $\delta^{13}C$ range is greater in females (females: 3.7‰, males: 3.1‰), the distribution of the data is very similar- both have a 'stingray-like' distribution and both have low-value outliers (Figure 71). Figure 72 shows some differences in the distribution of the enamel carbonate $\delta^{18}O$, but this is mostly due to the much larger sample size for the males.

There is one female outlier – PSN 728 from All Saints and three male outliers – PSN 225 from the Hospital detached cemetery and PSNs 731 and 734 from All Saints. The enamel $^{87}Sr/^{86}Sr$ values are almost identical in distribution by sex, with both showing heavy skewing towards the lower values, and both having high-value outliers (Figure 73). When the enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values are plotted together (Figure 74), there are some differences in the shape and distribution by sex, with the female values having a wider $\delta^{18}O$ range, and males having a slightly wider $^{87}Sr/^{86}Sr$ range. The inner bag is different between the sexes, with the core 50% of the males having slightly higher $^{87}Sr/^{86}Sr$ values, and higher $\delta^{18}O$ values than females.

Sex	***n***	**Dentine $\delta^{13}C$ (‰) (VPDB)**						**Dentine $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Female	63	-19.3	0.4	-19.4	-20.2	-18.1	2.1	11.8	1.1	12.0	9.3	13.9	4.6
Male	93	-19.2	0.4	-19.2	-20.0	-18.0	2.0	11.9	1.3	11.8	9.1	15.4	6.3
TOTAL	**156**												

Table 25: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

Sex	***n***	**Rib $\delta^{13}C$ (‰) (VPDB)**						**Rib $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Female	78	-19.3	0.4	-19.4	-20.1	-18.2	1.9	12.2	1.0	12.2	9.4	14.6	5.2
Male	136	-19.0	0.5	-19.1	-20.2	-17.5	2.7	12.6	1.2	12.6	9.5	15.2	5.7
TOTAL	**207**												

Table 26: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

Sex	**n**	**Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Female	67	-12.8	0.6	-12.7	-15.1	-11.4	3.7
Male	102	-12.8	0.6	-12.8	-14.9	-11.8	3.1
TOTAL	**169**						

Table 27: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

Sex	***n***	**Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)**						***Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)***					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Female	67	-5.1	1.0	-4.9	-8.0	-2.9	5.1	16.8	1.1	17.0	13.7	19.1	5.4
Male	102	-5.0	0.9	-4.8	-7.4	-2.4	5.0	16.9	0.9	17.1	14.3	19.6	5.3
TOTAL	**169**												

Table 28: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for adult High/Late Medieval Cambridgeshire individuals, by sex

Sex	**n**	**Enamel $^{87}Sr/^{86}Sr$**						**Sr ppm**	
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Female	50	0.7090	0.0007	0.7088	0.7081	0.7122	0.0041	130	32
Male	63	0.7090	0.0009	0.7087	0.7081	0.7134	0.0053	127	46
TOTAL	**113**								

Table 29: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

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

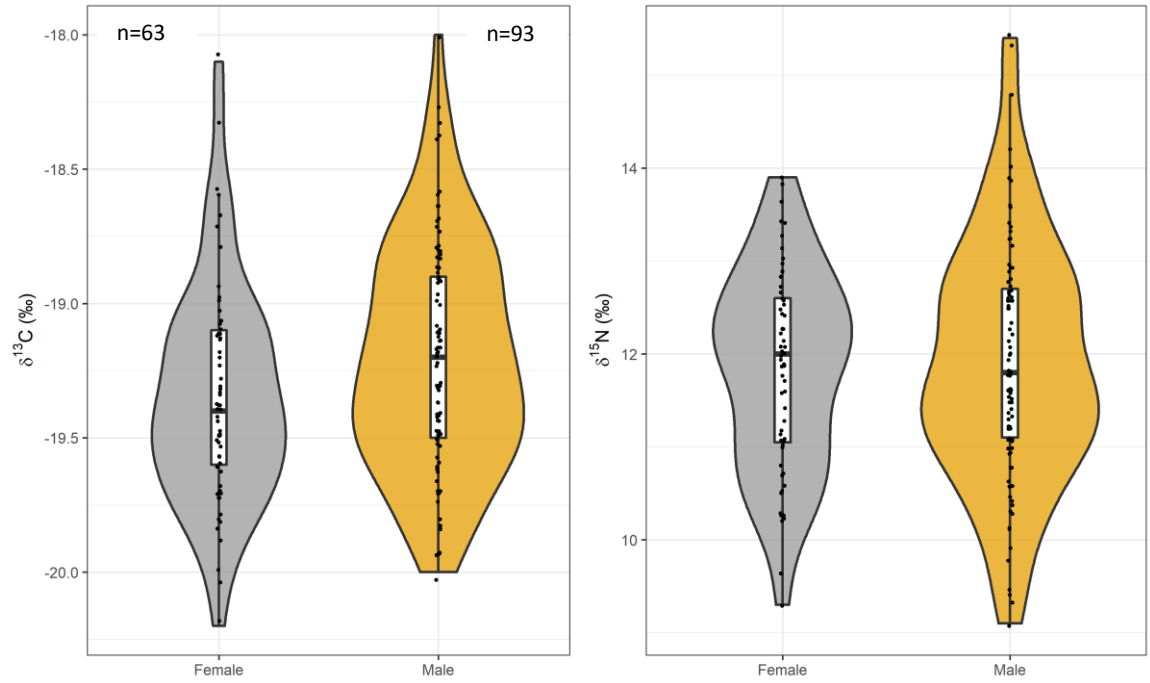


Figure 67: Violinplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate

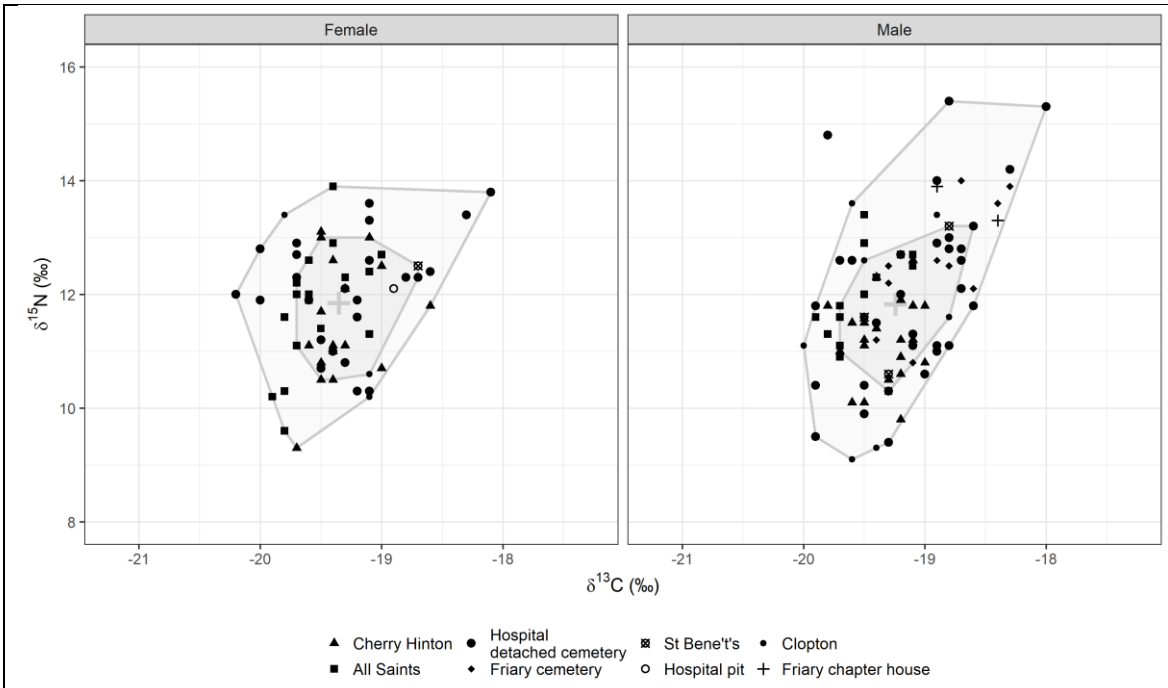


Figure 68: Bagplots with scatterplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

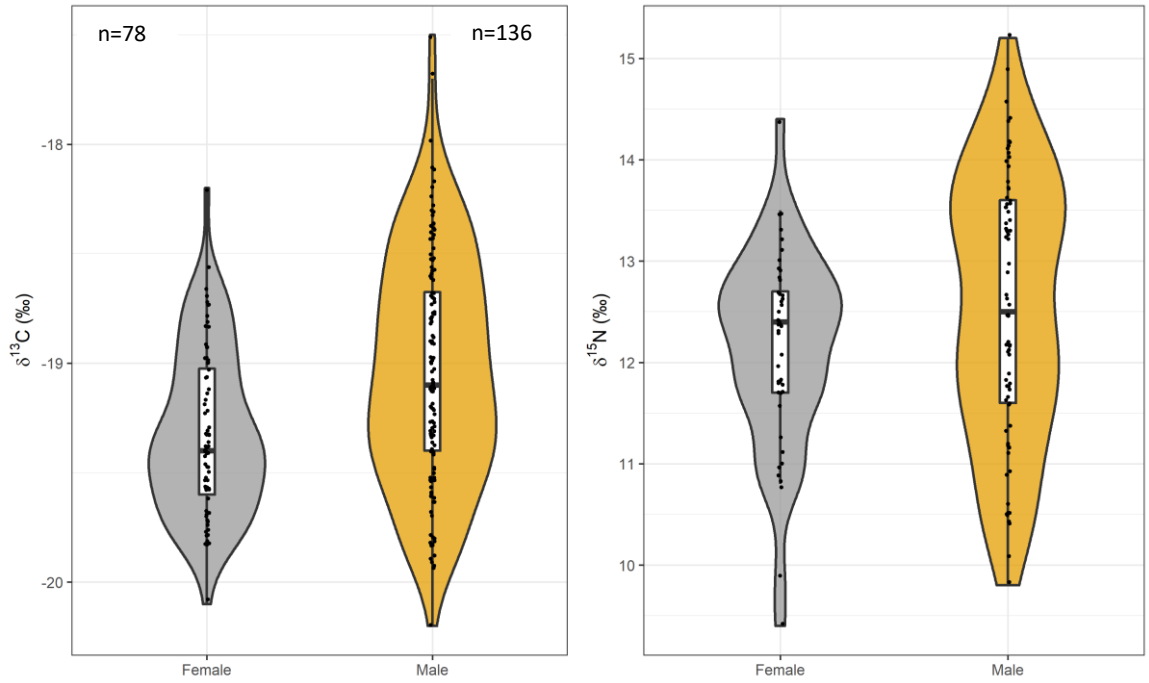


Figure 69: Violinplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate

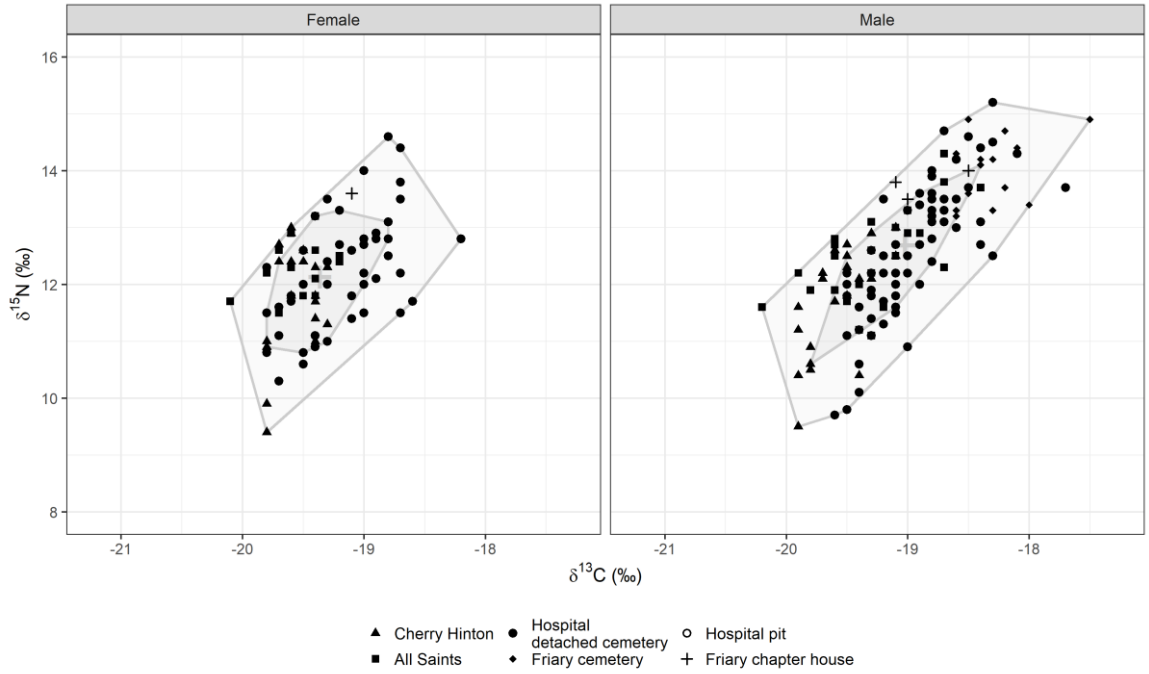


Figure 70: Bagplots with scatterplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

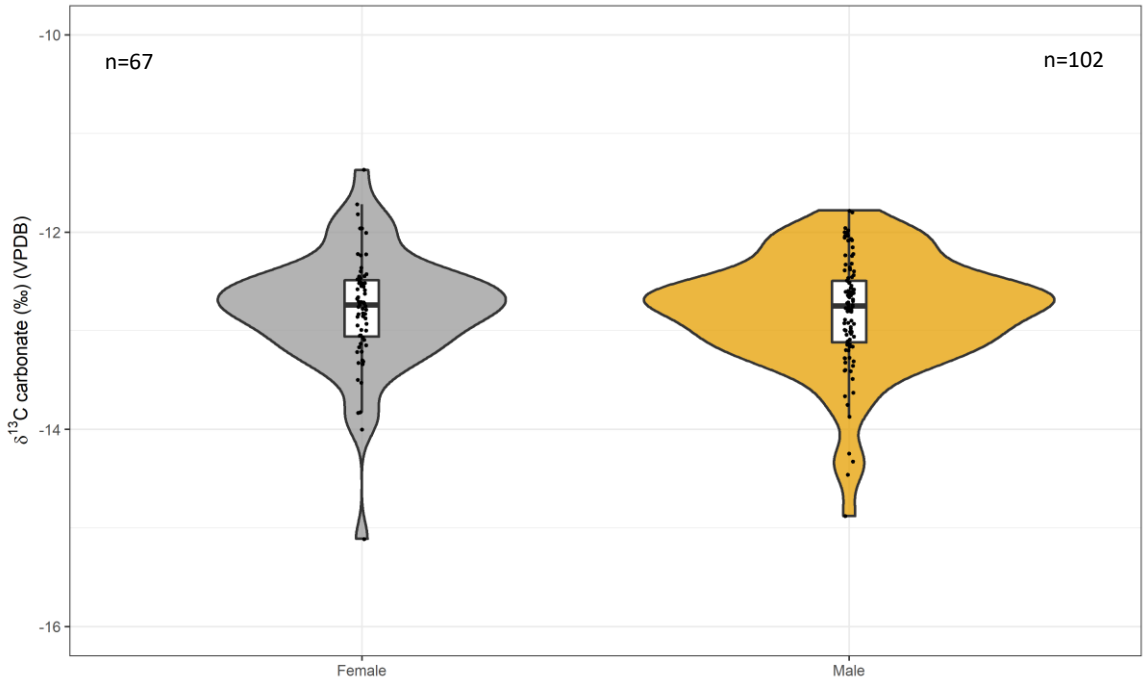


Figure 71: Violinplot showing tooth enamel carbonate $\delta^{13}C$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

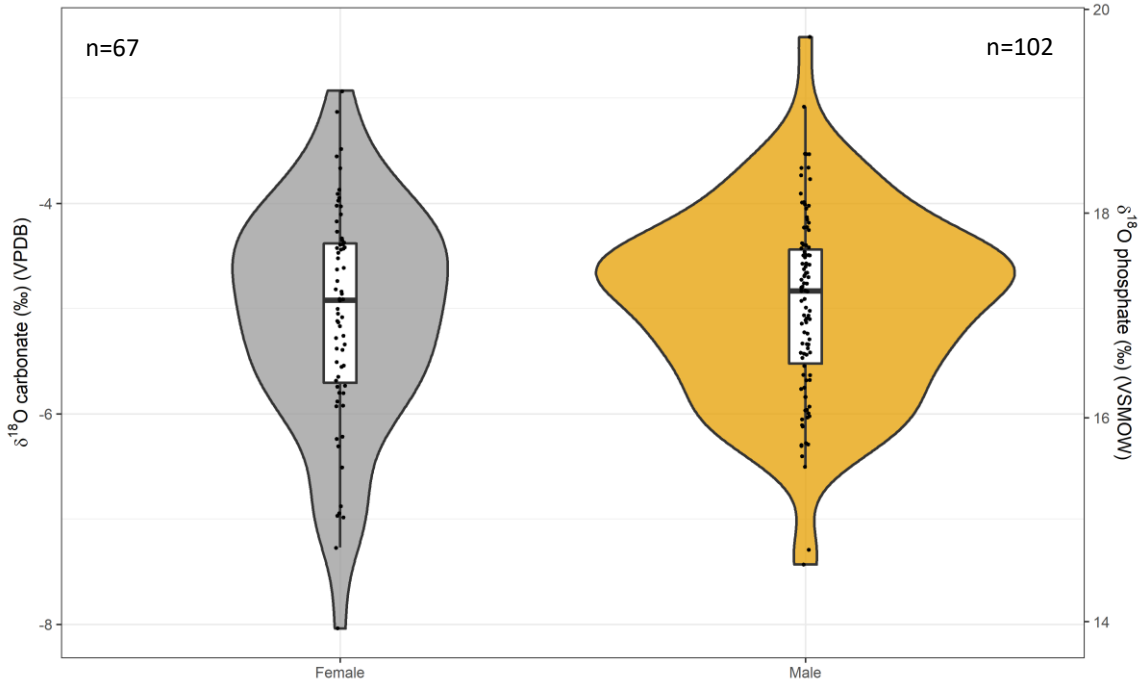


Figure 72: Violinplot showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for adult High/Late Medieval Cambridgeshire individuals, by sex

Enamel $^{87}Sr/^{86}Sr$

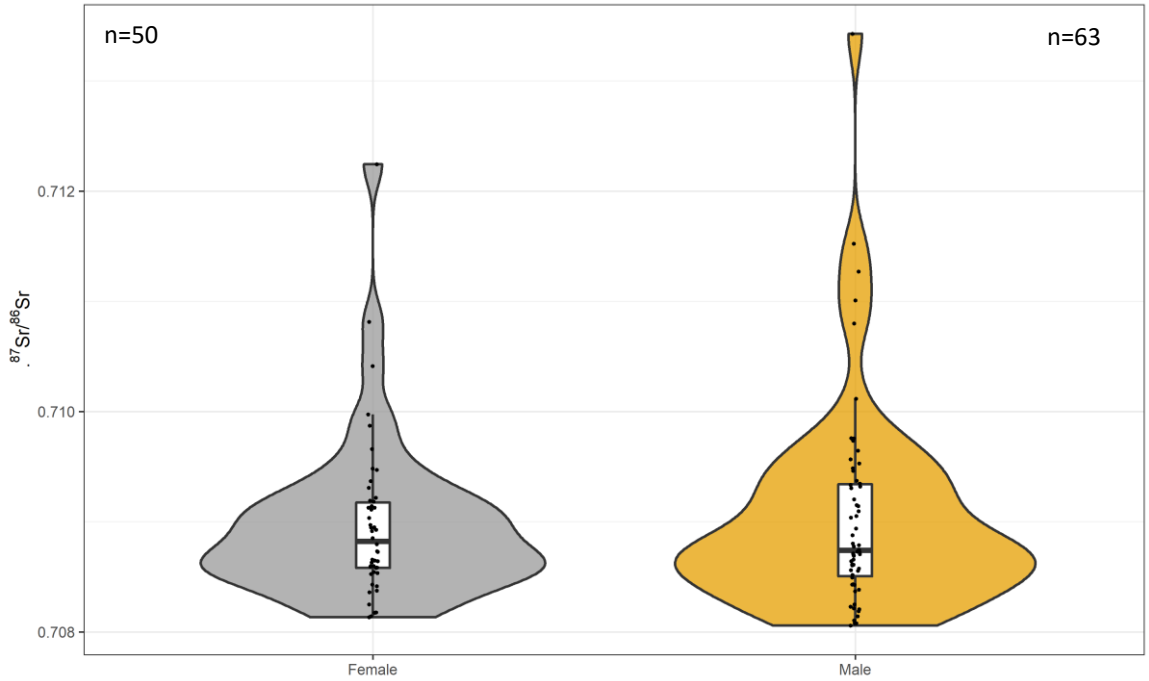


Figure 73: Violinplot showing tooth enamel $^{87}Sr/^{86}Sr$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

Enamel Carbonate $\delta^{18}O$ and Enamel $^{87}Sr/^{86}Sr$

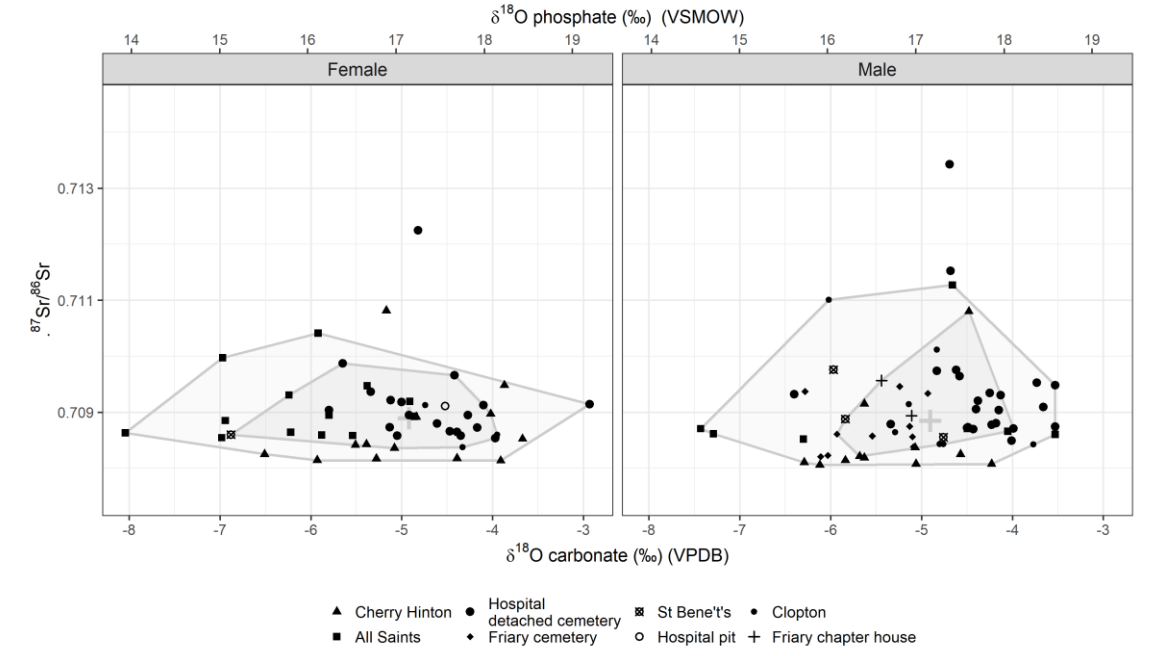


Figure 74: Bagplots showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) and enamel $^{87}Sr/^{86}Sr$ values for adult High/Late Medieval Cambridgeshire individuals, by sex

7.5.2 Results: Sex and Site Subgroup

There are some sex-based differences when the isotope data is broken down by site subgroup. (Table 30 to Table 34). There is general overlap in the distribution of the dentine $\delta^{13}C$ and $\delta^{15}N$ values by sex at each site, but there are differences in the probability densities, particularly at Cherry Hinton, where the female $\delta^{13}C$ values show a multimodal distribution and the male $\delta^{15}N$ values are more densely clustered (Figure 75). The Hospital detached cemetery shows the largest sex-based differences in mean rib collagen $\delta^{13}C$ and $\delta^{15}N$ values (except for the Hospital pit, but only one male and one female are represented), with males having 0.3‰ higher mean $\delta^{13}C$ values and 0.4‰ higher $\delta^{15}N$ values than females (Table 31). There are sex-based differences in the range of rib $\delta^{13}C$ and $\delta^{15}N$ values at each site, with males consistently having greater ranges (Table 31, Figure 76). There are some differences in the probability densities between sexes in rib $\delta^{13}C$ values at Cherry Hinton and All Saints, and a divergence in the $\delta^{13}C$ boxplots at the Hospital detached cemetery (Figure 76). Clopton appears to display a sex-based difference of 0.7‰ in enamel carbonate $\delta^{13}C$ values (female:-12.9‰, male:-13.6‰) (Table 32). This is further highlighted in Figure 77, where most sites with both males and females have a high degree of overlap, but at Clopton, the boxplots diverge.

More differences between the sexes are apparent in the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ data when it is broken down by site subgroup than by sex only (Table 33, Table 34, Figure 77, Figure 78). At All Saints, the mean $\delta^{18}O$ value for males is 0.6‰ higher than females, and at Clopton female mean values are 0.7‰ higher than males. The divergence in the boxplots at Clopton is particularly apparent in Figure 77. There is some clustering in the $^{87}Sr/^{86}Sr$ values by sex, with Cherry Hinton and All Saints having a very tight cluster of males with lower values, and females with more dispersed values (Figure 78). Clopton shows the reverse, with the females clustering with lower values and males being more dispersed, although this trend is less pronounced. Although most of the $^{87}Sr/^{86}Sr$ values for males and females at Cherry Hinton and All Saints are within the 'local' range estimated for Cambridge (0.7080-0.7100), the clustering could reveal some nuance in the data and could be indicative of more mobility in females than males.

Site Subgroup	*Sex*	*n*	Dentine δ13C (‰) (VPDB)						Dentine δ15N (‰) (AIR)					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	*F*	17	-19.3	0.3	-19.4	-19.7	-18.6	1.1	11.5	1.1	11.1	9.3	13.1	3.8
	M	22	-19.3	0.2	-19.4	-19.8	-19.0	0.8	11.2	0.7	11.2	9.8	12.6	2.8
All Saints	*F*	17	-19.5	0.3	-19.6	-19.9	-19.0	0.9	11.8	1.1	12.0	9.6	13.9	4.3
	M	14	-19.5	0.3	-19.5	-19.9	-19.1	0.8	11.9	0.9	11.9	10.3	13.4	3.1
Hospital detached cemetery	*F*	24	-19.3	0.5	-19.2	-20.2	-18.1	2.1	12.1	1.0	12.2	10.3	13.8	3.5
	M	31	-19.1	0.5	-19.0	-19.9	-18.0	1.9	12.1	1.6	12.0	9.4	15.4	6.0
Friary cemetery	*M*	13	-18.9	0.4	-18.9	-19.5	-18.3	1.2	12.4	1.0	12.5	10.8	14.0	3.2
St Bene't's	*F*	1	-18.7	-	-18.7	-18.7	-18.7	-	12.5	-	12.5	12.5	12.5	-
	M	3	-19.2	0.4	-19.3	-19.5	-18.8	0.7	11.8	1.3	11.6	10.6	13.2	2.6
Hospital pit	*F*	1	-18.9	-	-18.9	-18.9	-18.9	-	12.1	-	12.1	12.1	12.1	-
Clopton	*F*	3	-19.3	0.4	-19.1	-19.8	-19.1	0.7	11.4	1.7	10.6	10.2	13.4	3.2
	M	8	-19.3	0.4	-19.4	-20.0	-18.8	0.2	11.7	1.8	12.1	9.1	13.6	4.5
Friary chapter house	*M*	2	-18.6	0.4	-18.6	-18.9	-18.4	0.5	13.6	0.4	13.6	13.3	13.9	0.6

Table 30: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex. F=Female, M=Male.

Site Subgroup	*Sex*	*n*	Rib δ13C (‰) (VPDB)						Rib δ15N (‰) (AIR)					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	*F*	19	-19.6	0.2	-19.6	-19.8	-19.3	0.5	11.7	1.0	11.8	9.4	13.0	3.6
	M	25	-19.6	0.2	-19.7	-19.9	-19.1	0.8	11.5	1.0	11.7	9.5	13.0	3.5
All Saints	*F*	13	-19.5	0.3	-19.5	-20.1	-19.2	0.9	12.3	0.5	12.3	11.5	13.2	1.7
	M	25	-19.3	0.4	-19.3	-20.2	-18.4	1.8	12.5	0.8	12.5	11.1	14.3	3.2
Hospital detached cemetery	*F*	44	-19.2	0.4	-19.1	-19.8	-18.2	1.6	12.2	1.0	12.2	10.3	14.6	4.1
	M	63	-18.9	0.4	-18.9	-19.6	-17.7	1.9	12.6	1.2	12.7	9.7	15.2	5.5
Friary cemetery	*M*	19	-18.3	0.3	-18.4	-18.9	-17.5	1.4	14.0	0.5	14.1	13.2	14.9	1.7
Hospital pit	*F*	1	-19.4	-	-19.4	-19.4	-19.4	-	13.2	-	13.2	13.2	13.2	-
	M	1	-19.3	-	-19.3	-19.3	-19.3	-	12.2	-	12.2	12.2	12.2	-
Friary chapter house	*F*	1	-19.1	-	-19.1	-19.1	-19.1	-	13.6	-	13.6	13.6	13.6	-
	M	3	-18.9	0.3	-19.0	-19.1	-18.5	0.6	13.8	0.3	13.8	13.5	14.0	0.5

Table 31: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex

Site Subgroup	Sex	n	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	Female	17	-12.6	0.6	-12.5	-13.8	-11.4	2.4
	Male	22	-12.6	0.6	-12.4	-14.2	-11.8	2.4
All Saints	Female	19	-12.9	0.4	-12.8	-13.8	-12.0	1.8
	Male	15	-13.0	0.5	-12.9	-14.5	-12.3	2.2
Hospital detached cemetery	Female	26	-12.8	0.6	-12.6	-15.1	-11.7	3.4
	Male	38	-12.7	0.4	-12.7	-13.7	-12.0	1.7
Friary cemetery	Male	14	-12.7	0.2	-12.7	-13.0	-12.2	0.8
St Bene't's	Female	1	-12.7	-	-12.7	-12.7	-12.7	-
	Male	3	-13.1	0.4	-13.3	-13.4	-12.6	0.8
Hospital pit	Female	1	-13.1	-	-13.1	-13.1	-13.1	-
Clopton	Female	3	-12.9	1.0	-12.8	-14.0	-12.0	2.0
	Male	8	-13.6	0.7	-13.5	-14.9	-12.6	2.3
Friary chapter house	Male	2	-13.3	0.1	-13.3	-13.4	-13.3	0.1

Table 32: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex

Site Subgroup	Sex	n	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						***Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)***					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	Female	17	-4.9	0.8	-5.1	-6.5	-3.7	2.8	17.0	0.9	16.8	15.3	18.3	3.0
	Male	22	-5.1	0.6	-4.9	-6.3	-4.0	2.3	16.8	0.7	17.0	15.5	17.9	2.4
All Saints	Female	19	-5.9	1.1	-5.9	-8.0	-3.5	4.5	16.0	1.2	16.0	13.7	18.5	4.8
	Male	15	-5.3	1.1	-5.3	-7.4	-3.5	3.9	16.5	1.2	16.5	14.3	18.5	4.2
Hospital detached cemetery	Female	26	-4.6	0.7	-4.5	-5.8	-2.9	2.9	17.3	0.8	17.4	16.0	19.1	3.1
	Male	38	-4.4	0.8	-4.4	-6.4	-2.4	4.0	17.5	0.8	17.5	15.4	19.6	4.2
Friary cemetery	Male	14	-5.6	0.5	-5.6	-6.5	-4.9	1.6	16.2	0.5	16.3	15.3	17.0	1.7
St Bene't's	Female	1	-6.9	-	-6.9	-6.9	-6.9	-	14.9	-	14.9	14.9	14.9	-
	Male	3	-5.5	0.7	-5.8	-6.0	-4.8	1.2	16.3	0.7	16.0	15.9	17.2	1.3
Hospital pit	Female	1	-4.5	-	-4.5	-4.5	-4.5	-	17.4	-	17.4	17.4	17.4	-
Clopton	Female	3	-4.3	0.4	-4.3	-4.7	-4.0	0.7	17.6	0.4	17.6	17.2	18.0	0.8
	Male	8	-5.0	0.6	-4.9	-6.0	-3.8	2.2	16.9	0.7	17.0	15.8	18.2	2.4
Friary chapter house	Male	2	-5.3	0.2	-5.3	-5.4	-5.1	0.3	16.6	0.2	16.6	16.4	16.8	0.4

Table 33: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex

Site Subgroup	Sex	n	Enamel $^{87}Sr/^{86}Sr$						Sr ppm	
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Cherry Hinton	Female	13	0.7087	0.0008	0.7084	0.7081	0.7108	0.0027	123	38
	Male	12	0.7085	0.0008	0.7082	0.7081	0.7108	0.0027	139	39
All Saints	Female	13	0.7091	0.0006	0.7089	0.7085	0.7104	0.0019	133	25
	Male	6	0.7091	0.0011	0.7086	0.7085	0.7113	0.0028	164	54
Hospital detached cemetery	Female	19	0.7092	0.0008	0.7089	0.7085	0.7122	0.0037	131	33
	Male	23	0.7094	0.0011	0.7091	0.7085	0.7134	0.0049	117	35
Friary cemetery	Male	10	0.7087	0.0005	0.7086	0.7082	0.7095	0.0013	118	52
St Bene't's	Female	1	0.7086	-	0.7086	0.7086	0.7086	0.0000	91	-
	Male	3	0.7091	0.0006	0.7089	0.7086	0.7098	0.0012	116	46
Hospital pit	Female	1	0.7091	-	0.7091	0.7091	0.7091	0.0000	107	-
Clopton	Female	3	0.7087	0.0004	0.7086	0.7084	0.7091	0.0007	153	25
	Male	7	0.7092	0.0010	0.7086	0.7084	0.7110	0.0026	129	70
Friary chapter house	Male	2	0.7093	0.0004	0.7093	0.7089	0.7096	0.0007	97	7

Table 34: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex

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

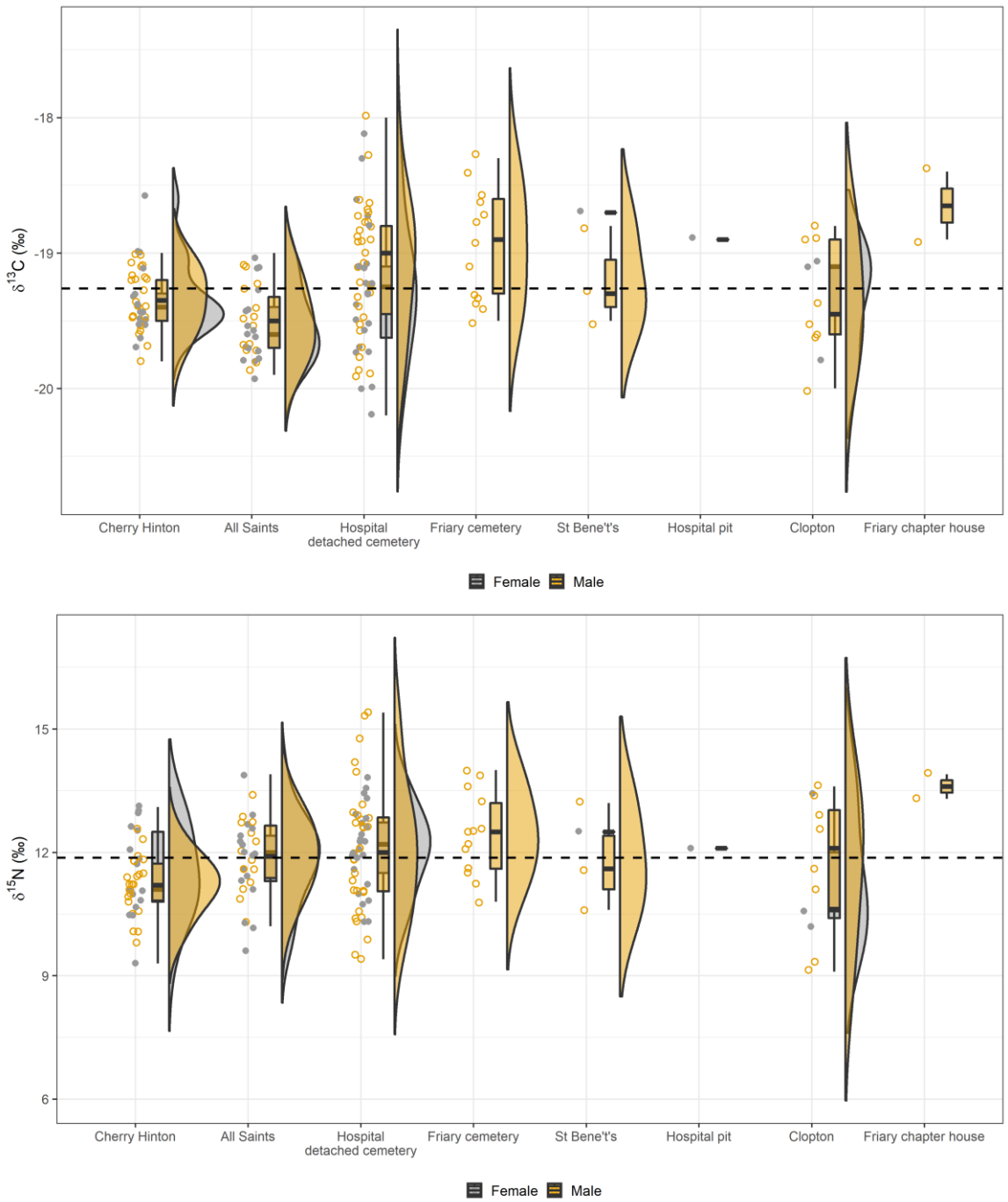


Figure 75: Raincloud plots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

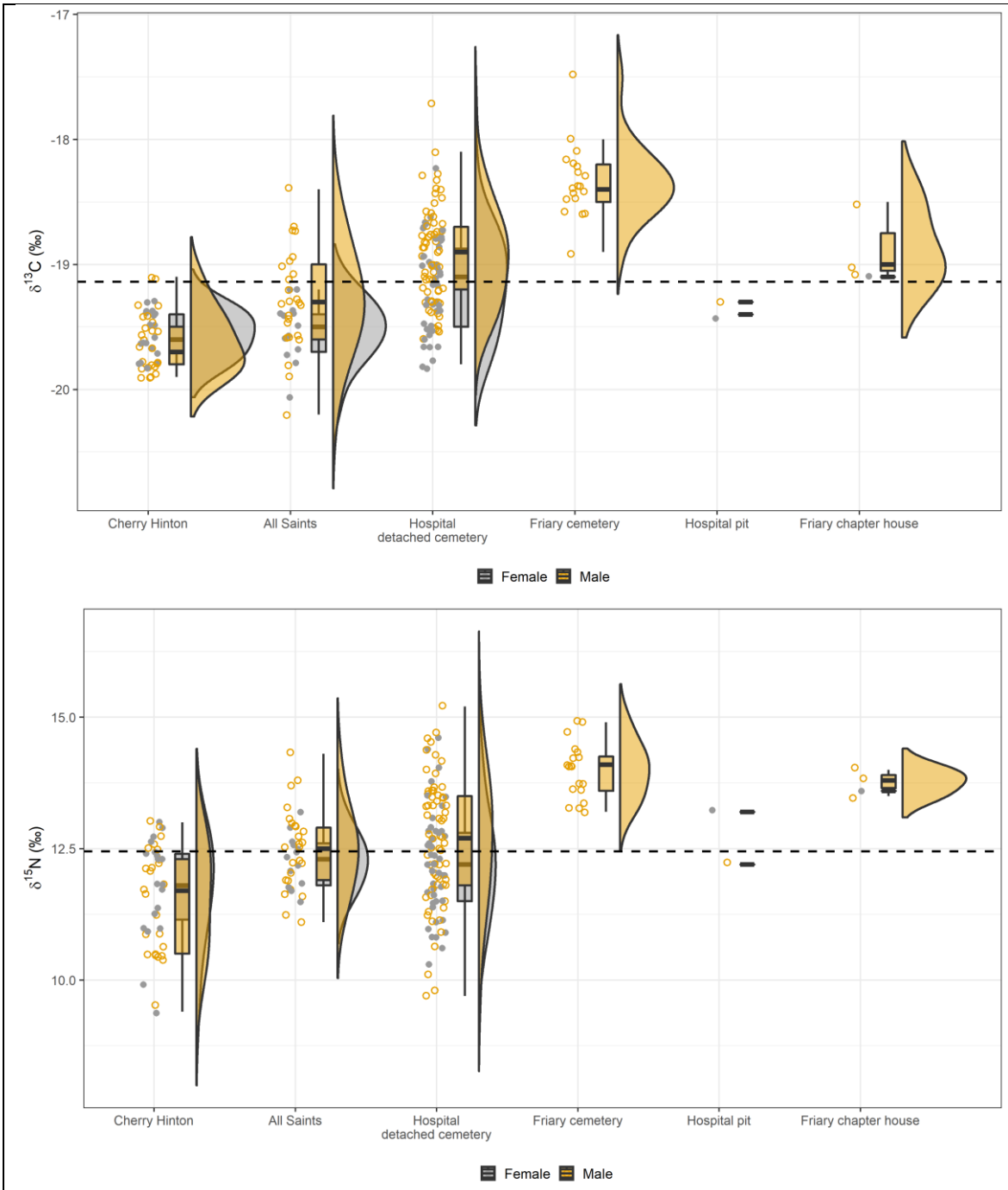


Figure 76: Raincloud plots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a female/male sex estimate, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

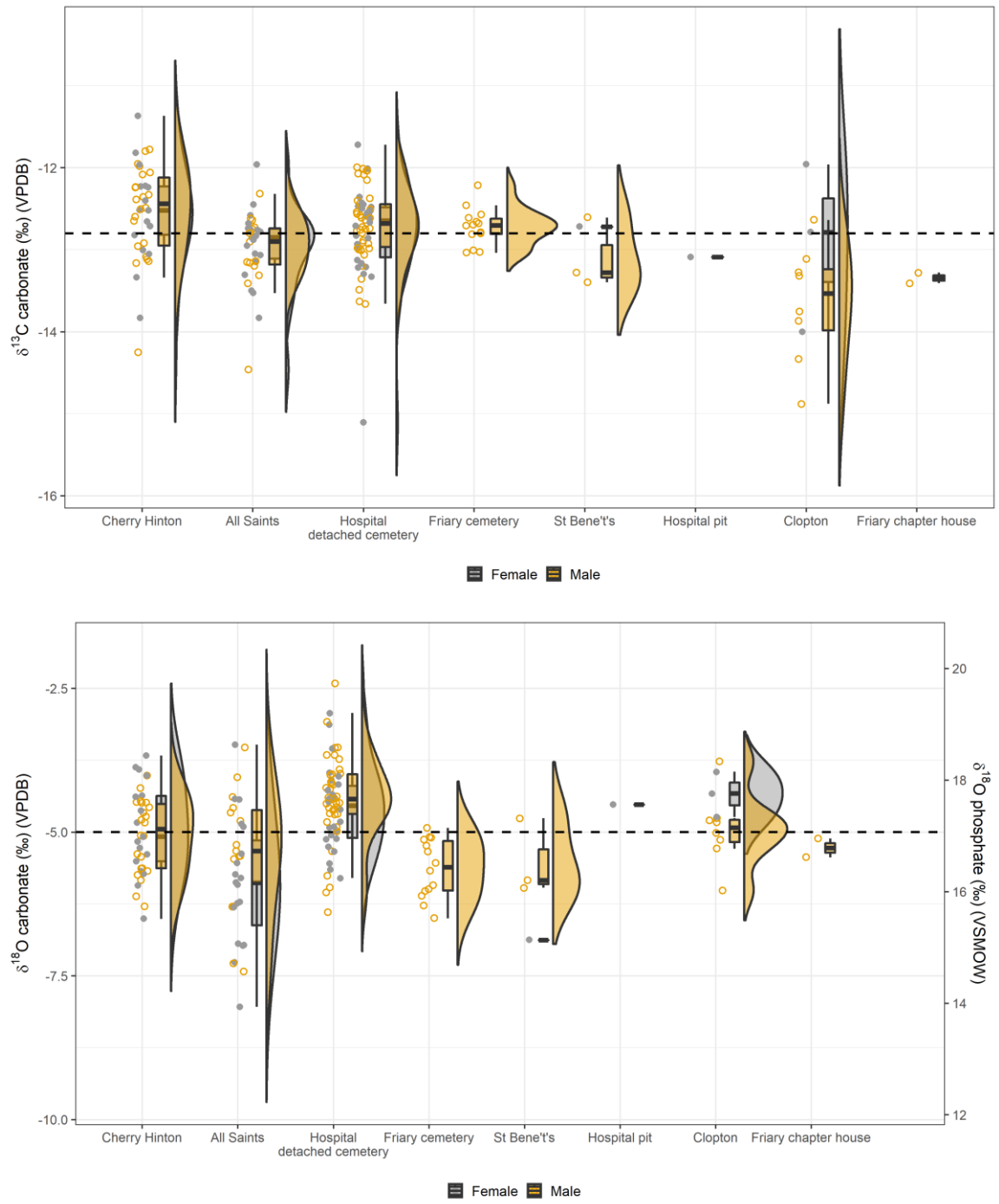


Figure 77: Raincloud plot showing tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Enamel $^{87}Sr/^{86}Sr$

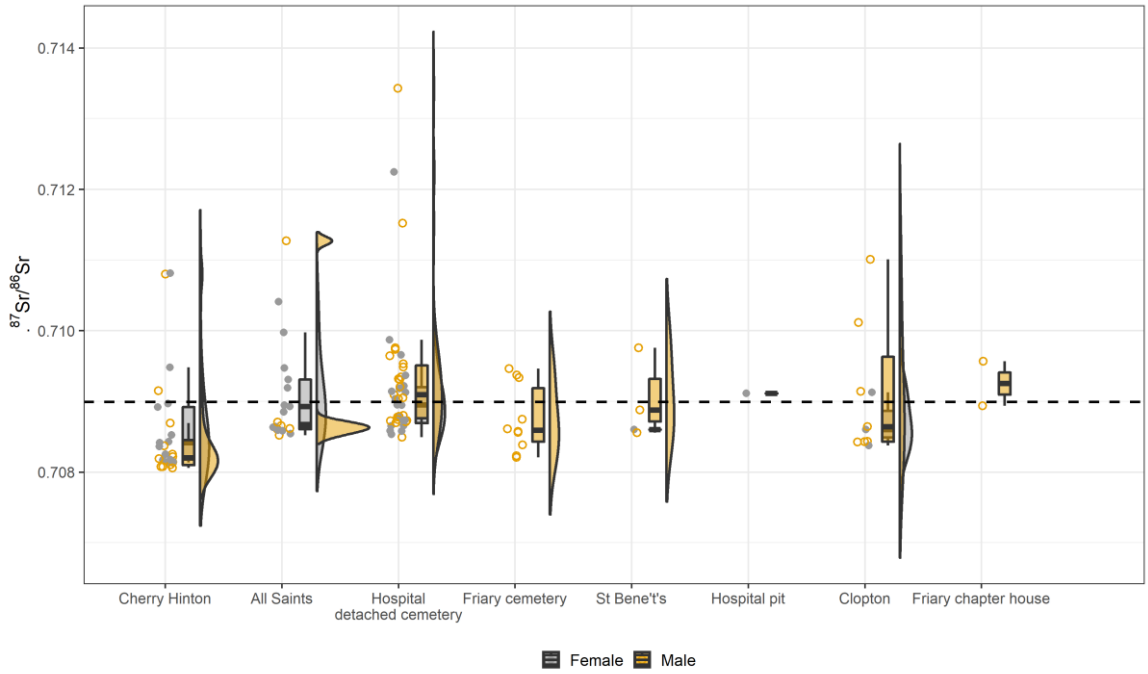


Figure 78: Raincloud plot showing tooth enamel $^{87}Sr/^{86}Sr$ values for adult High/Late Medieval Cambridgeshire individuals, by site subgroup and sex. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

7.5.3 Statistical Testing: Sex Only

Comparison of isotope values for High/Late individuals by sex show that dentine collagen $\delta^{13}C$ values, adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ values were unlikely to be taken from populations with equal medians (Wilcoxon rank-sum tests: dentine $\delta^{13}C$: p=0.0443; rib $\delta^{13}C$ p=<0.0001; rib $\delta^{15}N$ p=0.0025).

7.5.4 Summary of High/Late Medieval Isotope Results by Sex

The results indicate that when grouped by sex alone, potentially meaningful differences were only seen in dentine collagen $\delta^{13}C$ values and adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ values. However, the differences in the rib collagen isotope values are likely to be largely driven by high $\delta^{13}C$ and $\delta^{15}N$ values in males in the Friary.

When analysed by site subgroup and sex, the patterns are more nuanced, particularly if the distribution of the data is considered, rather than summary statistics. Cherry Hinton and the Hospital detached cemetery show much more divergence between male and female dentine $\delta^{13}C$ and $\delta^{15}N$ values than at other sites. All sites with substantial numbers of males and females showed some divergence in rib collagen isotope values by sex, particularly for $\delta^{13}C$. The distribution of the enamel carbonate $\delta^{13}C$ data is remarkably similar between sexes for all sites with substantial sample numbers.

It is not clear how to interpret these two patterns of $\delta^{13}C$ data together, as enamel $\delta^{13}C$ could be reflective of whole diet and dentine $\delta^{13}C$ could be reflective of the dietary protein (Ambrose and Norr 1993, Tieszen and Fagre 1993), but both should represent diet during the period of tooth formation. Either diet was less divergent in earlier childhood, when the tooth enamel was forming, or the foods which are driving the divergence in the dentine collagen are not proportionately routed to the enamel carbonate. Overall, the data either indicates that the sampled females and males experienced different diets, with varying access to animal and marine proteins and/or there are unaccounted physiological differences between females and males that result in variable isotopic signatures. Although a small sample, the distribution of the dentine collagen and enamel carbonate $\delta^{13}C$ values of the three females present at Clopton is unusual and driving an apparently large difference between the male and female distribution at

the site. Without a larger sample, it is unfortunately difficult to interpret, but it is likely that these three females are not representative of the whole female population from Clopton.

There is no meaningful difference in enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values by sex only. There are both females and males with outlying $^{87}Sr/^{86}Sr$ values, indicating that there was some population mobility, but it was not predominated by one sex. When considered by sex and site subgroup, there may be some sex-based differences, with All Saints showing some difference in both $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ by sex, and Cherry Hinton also showing differences in $^{87}Sr/^{86}Sr$ by sex. Although most values are still within the estimated 'local' range for Cambridge, this could indicate there was more short-range sex-based diversity in where people buried at All Saints and Cherry Hinton spent their childhoods than at other sites.

7.6 High/Late Medieval Human Isotope Results by Social Group

The section investigates the High/Late Medieval individuals by broad social groups. These are primarily grouped by site type: the Friary and Hospital are considered distinct groups, All Saints represents the 'parish' group, Clopton and Cherry Hinton are combined as the 'rural' group and St Bene't's is considered a 'mass burial'. These are then sub-divided by adult/non-adult, adult sex and those explicitly identified as Friars (distinguished from the lay people buried in the Friary). For the purposes of this section 'social group' will refer to the overall grouping, e.g. 'rural females', 'site group' will refer to the primary site type, e.g. 'rural' and 'subgroup' will refer to the subdivisions, e.g. male/female. Separation by these categories allows for more nuance in the data analysis and allows for some intersectional comparisons by considering location, sex and age in the groupings.

7.6.1 Results: Social Group

There are differences in the mean, median and range of the $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values between the social groups, but not $^{87}Sr/^{86}Sr$ values (Table 35 to Table 39). When considered by sex, there are relatively large differences, for example the mean male dentine $\delta^{15}N$ values vary by up to 2.1‰: Friars= 12.3‰, Friary males= 13.4‰, Hospital males= 12.1‰, Parish males= 11.9‰, Rural males= 11.3‰ and Mass burial males= 11.8‰. However, Figure 79 to Figure 81 highlight that while there appears to be a lot of variation between the social groups, in most cases the differences between the site groups, e.g. 'rural' vs 'Hospital' tend to outweigh the intra-site group differences, e.g. male/female/nonadult.

Despite this, the Friary and rural non-adult groups do have noticeably lower dentine $\delta^{15}N$ values than adults in their site group but also out of all of the High/Late Medieval individuals (Figure 79). The non-adults are also distinct in their mean dentine $\delta^{13}C$ values, with the Friary non-adults being much lower and the rural non-adults being higher than the mean values for other groups.

The rib collagen $\delta^{13}C$ range is also very different between parish males and females. The parish females show the largest $\delta^{18}O$ range (4.5‰) and the rural non-adults show the least (0.5‰) (Table 38). Rural non-adults also have the lowest mean and median $^{87}Sr/^{86}Sr$ values (Table 39).

While most of the $^{87}Sr/^{86}Sr$ are within the 'local' range, the parish males are distinctive in their distribution and their contrast to the distribution to parish females (Figure 82).

Analysis by social group highlights several trends: first, the Friary groups are distinct from the other groups in their $\delta^{13}C$ and $\delta^{15}N$ values and there is also stratification within the Friary. There is a relatively large difference in the mean dentine $\delta^{13}C$ and $\delta^{15}N$ values between Friars and Friary males, particularly in $\delta^{15}N$ values (Friars: 12.3‰, Friary males: 13.4‰) but the rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for the Friars and Friary males are more similar. The Friary non-adults also have very different values to the adults. The one female analysed from the Friary has rib collagen $\delta^{15}N$ values on par with the Friars, although her $\delta^{13}C$ value is lower, and is distinct from females in other groups. Second, there appears to be more differences between males and females in the parish than in other site groups, perhaps indicating more dietary differences, and/or more social mobility by sex.

Group	*n*	**Dentine $\delta^{13}C$ (‰) (VPDB)**						**Dentine $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Friars	14	-19.0	0.4	-19.0	-19.5	-18.3	1.2	12.3	1.2	12.3	9.8	13.9	4.1
Friary males	3	-18.6	0.2	-18.7	-18.8	-18.4	0.4	13.4	0.8	13.6	12.5	14.0	1.5
Friary nonadults	3	-19.7	0.4	-19.7	-20.0	-19.3	0.7	11.1	2.8	9.8	9.3	14.3	5.0
Hospital females	25	-19.3	0.5	-19.2	-20.2	-18.1	2.1	12.1	1.0	12.1	10.3	13.8	3.5
Hospital males	31	-19.1	0.5	-19.0	-19.9	-18.0	1.9	12.1	1.6	12.0	9.4	15.4	6.0
Parish females	17	-19.5	0.3	-19.6	-19.9	-19.0	0.9	11.8	1.1	12.0	9.6	13.9	4.3
Parish males	14	-19.5	0.3	-19.5	-19.9	-19.1	0.8	11.9	0.9	11.9	10.3	13.4	3.1
Rural females	20	-19.3	0.3	-19.4	-19.8	-18.6	1.2	11.5	1.1	11.1	9.3	13.4	4.1
Rural males	30	-19.3	0.3	-19.4	-20.0	-18.8	1.2	11.3	1.1	11.3	9.1	13.6	4.5
Rural nonadults	2	-19.4	0.1	-19.4	-19.5	-19.3	0.2	10.6	2.1	10.6	9.1	12.0	2.9
Mass burial females	1	-18.7	-	-18.7	-18.7	-18.7	-	12.5	-	12.5	12.5	12.5	-
Mass burial males	3	-19.2	0.4	-19.3	19.5	-18.8	0.7	11.8	1.3	11.6	10.6	13.2	2.6
TOTAL	**163**												

Table 35: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by social group

Group	*n*	**Rib $\delta^{13}C$ (‰) (VPDB)**						**Rib $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Friars	18	-18.4	0.4	-18.4	-19.1	-17.5	1.6	13.9	0.5	13.8	13.3	14.9	1.6
Friary females	1	-19.1	-	-19.1	-19.1	-19.1	-	13.6	-	13.6	13.6	13.6	-
Friary males	5	-18.4	0.1	-18.4	-18.6	-18.2	0.4	14.1	0.5	14.1	13.2	14.7	1.5
Friary nonadults	4	-19.2	0.7	-19.4	-19.7	-18.3	1.4	12.8	1.6	13.3	10.6	14.2	3.6
Hospital females	45	-19.2	0.4	-19.1	-19.8	-18.2	1.6	12.3	1.0	12.2	10.3	14.6	4.3
Hospital males	64	-18.9	0.4	-18.9	-19.6	-17.7	1.9	12.6	1.2	12.7	9.7	15.2	5.5
Hospital adults	7	-18.9	0.4	-18.8	-19.4	-18.4	1.0	12.4	1.1	12.6	10.2	13.8	3.6
Hospital nonadults	37	-19.1	0.4	-19.1	-19.9	-18.3	1.6	11.8	1.4	11.9	8.3	14.1	5.8
Parish females	13	-19.5	0.3	-19.5	-20.1	-19.2	0.9	12.3	0.5	12.3	11.5	13.2	1.7
Parish males	25	-19.3	0.4	-19.3	-20.2	-18.4	1.8	12.5	0.8	12.5	11.1	14.3	3.2
Parish adults	2	-19.6	0.1	-19.6	-19.7	-19.6	0.1	11.6	0.3	11.6	11.4	11.8	0.4
Parish nonadults	3	-19.6	0.2	-19.6	-19.8	-19.5	0.3	12.5	0.5	12.4	12.0	13.0	1.0
Rural females	19	-19.6	0.2	-19.6	-19.8	-19.3	0.5	11.7	1.0	11.8	9.4	13.0	3.6
Rural males	25	-19.6	0.2	-19.7	-19.9	-19.1	0.8	11.5	1.0	11.7	9.5	13.0	3.5
Rural adults	1	-19.6	-	-19.6	-19.6	-19.6	-	12.8	-	12.8	12.8	12.8	-
Rural nonadults	15	-19.6	0.3	-19.7	-20.0	-19.0	1.0	11.4	1.5	12.1	8.2	13.2	5.0
TOTAL	**284**												

Table 36: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by social group

Social Group	***n***	**Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Friars	15	-12.9	0.3	-12.8	-13.4	-12.5	0.9
Friary males	3	-12.7	0.4	-12.8	-13.0	-12.2	0.8
Friary nonadults	3	-13.4	0.0	-13.4	-13.5	-13.4	0.1
Hospital females	27	-12.8	0.6	-12.7	-15.1	-11.7	3.4
Hospital males	38	-12.7	0.4	-12.7	-13.7	-12.0	1.7
Hospital nonadults	19	-12.6	0.3	-12.7	-13.2	-11.9	1.3
Parish females	19	-12.9	0.4	-12.8	-13.8	-12.0	1.8
Parish males	15	-13.0	0.5	-12.9	-14.5	-12.3	2.2
Rural females	20	-12.6	0.6	-12.6	-14.0	-11.4	2.6
Rural males	30	-12.8	0.8	-12.6	-14.9	-11.8	3.1
Rural nonadults	2	-12.2	0.4	-12.2	-12.4	-11.9	0.5
Mass burial females	1	-12.7	-	-12.7	-12.7	-12.7	-
Mass burial males	3	-13.1	0.4	-13.3	-13.4	-12.6	0.8
TOTAL	**195**						

Table 37: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for all High/Late Medieval Cambridgeshire individuals, by social group

Social Group	***n***	**Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)**						***Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)***					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Friars	15	-5.6	0.5	-5.5	-6.5	-5.1	1.4	16.3	0.5	16.3	15.3	16.8	1.5
Friary males	3	-5.4	0.6	-5.2	-6.1	-4.9	1.2	16.4	0.7	16.6	15.7	17.0	1.3
Friary nonadults	3	-4.9	1.3	-4.2	-6.4	-4.1	2.3	17.0	1.4	17.7	15.5	17.9	2.4
Hospital females	27	-4.6	0.7	-4.5	-5.8	-2.9	2.9	17.3	0.8	17.4	16.0	19.1	3.1
Hospital males	38	-4.4	0.8	-4.4	-6.4	-2.4	4.0	17.5	0.8	17.5	15.4	19.6	4.2
Hospital nonadults	19	-4.8	0.9	-5.1	-6.1	-3.4	2.7	17.1	1.0	16.8	15.8	18.6	2.8
Parish females	19	-5.9	1.1	-5.9	-8.0	-3.5	4.5	16.0	1.2	16.0	13.7	18.5	4.8
Parish males	15	-5.3	1.1	-5.3	-7.4	-3.5	3.9	16.5	1.2	16.5	14.3	18.5	4.2
Rural females	20	-4.8	0.8	-4.8	-6.5	-3.7	2.8	17.1	0.8	17.1	15.3	18.3	3.0
Rural males	30	-5.0	0.6	-4.9	-6.3	-3.8	2.5	16.9	0.7	17.0	15.5	18.2	2.7
Rural nonadults	2	-5.5	0.4	-5.5	-5.7	-5.2	0.5	16.4	0.4	16.4	16.1	16.7	0.6
Mass burial females	1	-6.9	-	-6.9	-6.9	-6.9	-	14.9	-	14.9	14.9	14.9	-
Mass burial males	3	-5.5	0.7	-5.8	-6.0	-4.8	1.2	16.3	0.7	16.0	15.9	17.2	1.3
TOTAL	**195**												

Table 38: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all High/Late Medieval Cambridgeshire individuals, by social group

Social Group	***n***	**Enamel $^{87}Sr/^{86}Sr$**						**Sr ppm**	
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Friars	11	0.7087	0.0004	0.7086	0.7082	0.7096	0.0014	109	47
Friary males	3	0.7090	0.0007	0.7093	0.7082	0.7095	0.0013	125	45
Friary nonadults	1	0.7091	-	0.7091	0.7091	0.7091	0.0000	79	-
Hospital females	20	0.7092	0.0008	0.7090	0.7085	0.7122	0.0037	130	32
Hospital males	23	0.7094	0.0011	0.7091	0.7085	0.7134	0.0049	117	35
Hospital nonadults	4	0.7089	0.0003	0.7089	0.7085	0.7092	0.0007	91	29
Parish females	13	0.7091	0.0006	0.7089	0.7085	0.7104	0.0019	133	25
Parish males	6	0.7091	0.0011	0.7086	0.7085	0.7113	0.0028	164	54
Rural females	16	0.7087	0.0007	0.7084	0.7081	0.7108	0.0027	129	37
Rural males	19	0.7088	0.0009	0.7084	0.7081	0.7110	0.0029	135	51
Rural nonadults	2	0.7083	0.0002	0.7083	0.7082	0.7084	0.0002	180	69
Mass burial females	1	0.7086	-	0.7086	0.7086	0.7086	0.0000	91	-
Mass burial males	3	0.7091	0.0006	0.7089	0.7086	0.7098	0.0012	116	46
TOTAL	**122**								

Table 39: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals, by social group

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

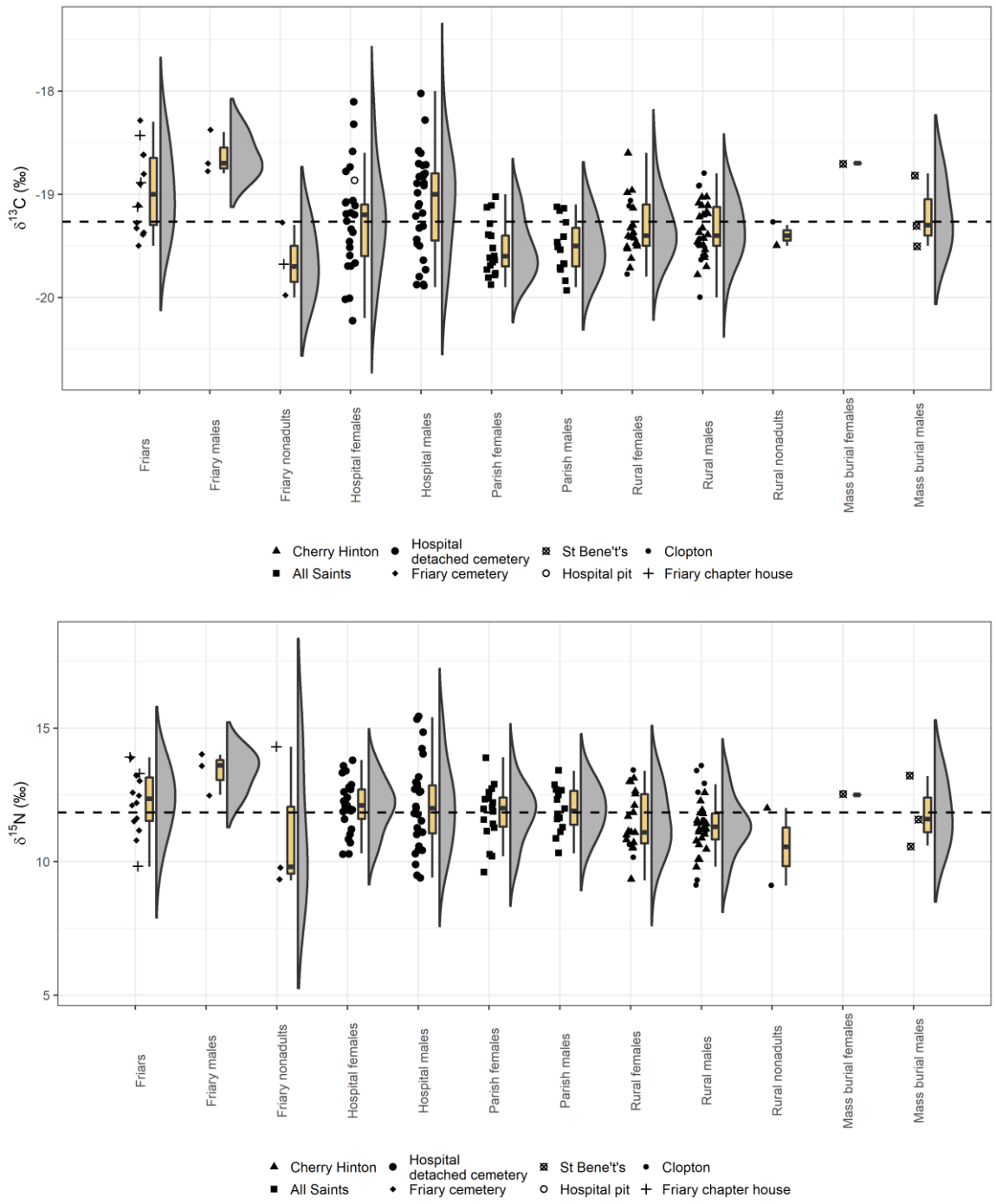


Figure 79: Raincloud plots of dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals, by social group. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

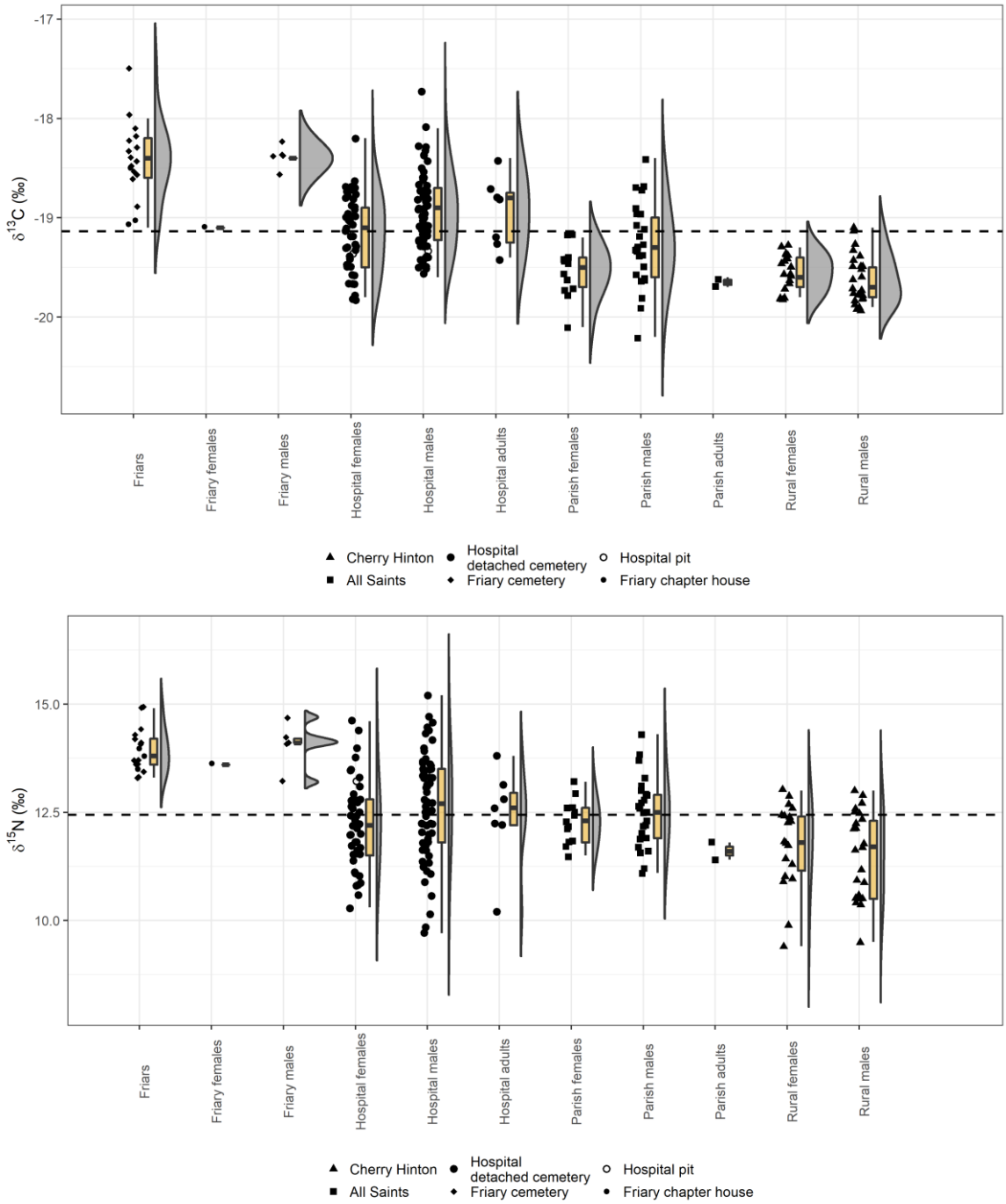


Figure 80: Raincloud plots of rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for all High/Late Medieval Cambridgeshire individuals, by social group. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

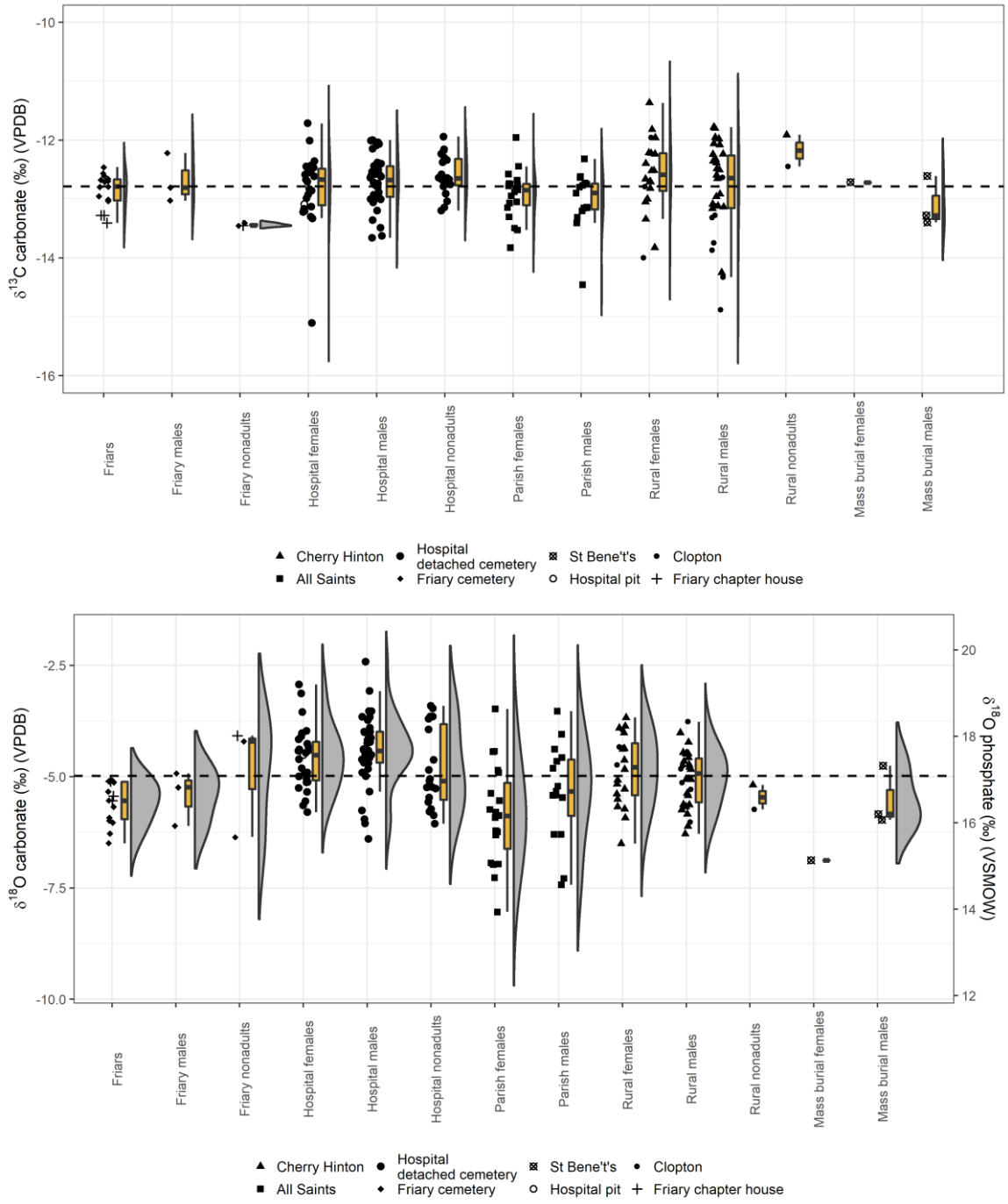


Figure 81: Raincloud plot of tooth enamel carbonate $\delta^{13}C$ and $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all High/Late Medieval Cambridgeshire individuals, by social group. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Enamel $^{87}Sr/^{86}Sr$

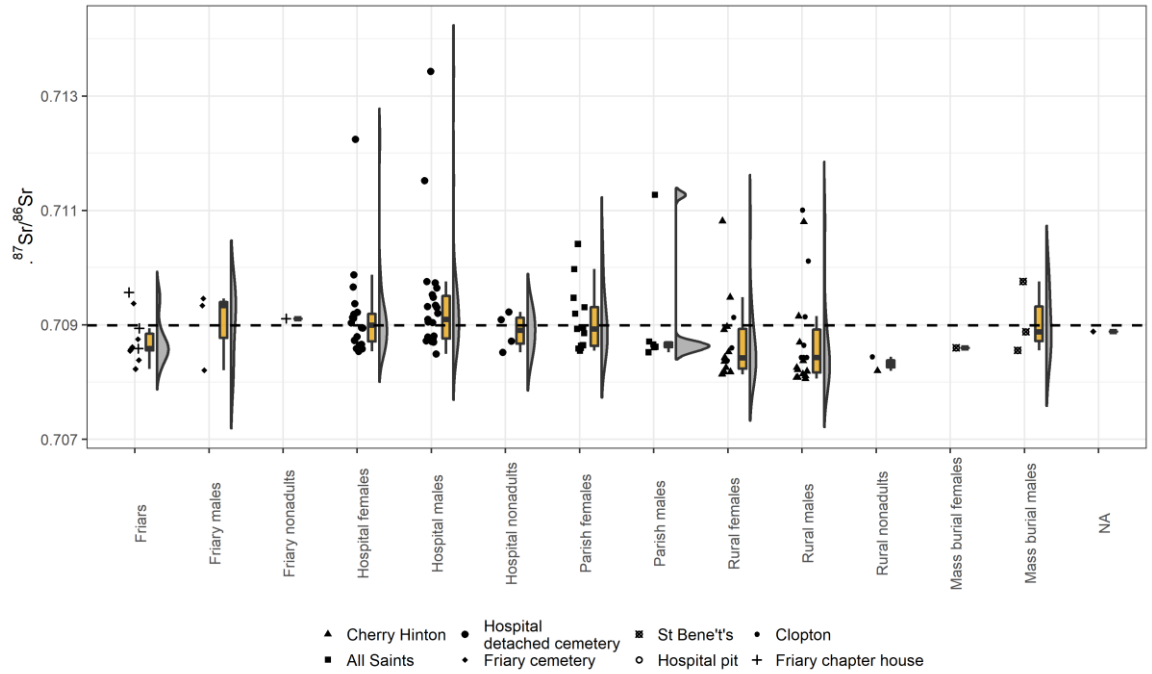


Figure 82: Raincloud plot showing tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals, by social group. Dashed line indicates the mean isotope value for all the individuals represented in the plot.

7.6.2 Statistical Testing: Social Group

Comparisons of the High/Late Medieval isotope values by social group show that all values except dentine collagen $\delta^{15}N$ are unlikely to be taken from populations with equal means (one-way ANOVA: enamel carbonate $\delta^{18}O$: p=<0.0001; Kruskal-Wallis tests: dentine collagen $\delta^{13}C$: p=<0.0001; rib collagen $\delta^{13}C$ and $\delta^{15}N$: p=<0.0001, enamel carbonate $\delta^{13}C$: p=0.0214). Post-hoc tests show a substantial number of pairwise comparisons indicating differences between social groups (see Appendix VI). The $\delta^{13}C$ and $\delta^{15}N$ comparisons show inter-group comparisons but no intra-group comparisons with *p.adj* values <0.05, indicating that location dominates over age or sex in the comparisons. Rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for the Friars appear to be different to almost every other non-Friary group, urban and rural. This is perhaps unsurprising for the Friars as they are a specialist institution and are most likely to follow a specialist diet (Woolgar 2006b, 2016, see Chapter 2). There are no pairwise comparisons between parish and rural groups that produce *p.adj* values <0.05. Tukey's post-hoc tests of $\delta^{18}O$ by social group shows multiple pairwise comparisons with *p.adj* values <0.05 (see Appendix VI). In particular, groups from the Hospital appear to differ from parish groups. Five of the eight pairwise comparisons with *p.adj* values <0.05 are between parish females and other groups, showing that the mean $\delta^{18}O$ value for parish females is different from many other groups in Cambridgeshire.

7.6.3 Summary: Social Group

There are meaningful differences in the $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ data by social group. The statistics and plots show that there are greater inter-site group differences in rib collagen $\delta^{13}C$ and $\delta^{15}N$ values than in dentine, indicating greater differences in diet in adulthood than childhood, which could be related to social status and lifecourse (Sealy *et al.* 1995). From the plots, there does appear to be differences in the sub-group isotope values, e.g. males/females in each site group, but these are not borne out in statistical testing and analysis shows that inter-site group differences far outweigh intra-site group differences. The greatest difference in $\delta^{13}C$ and $\delta^{15}N$ values is between the Friars and most other social groups, indicating a specialist institutionalised diet. For $^{87}Sr/^{86}Sr$, there are outliers in every adult social group that has a sample size >3, indicating that there is not a meaningful difference in the number of potential 'non-locals' by social group. Overall, analysis of the data by social group shows the presence of differences

primarily based on affiliation with a religious institution and between groups based within the town or more rural locations.

7.7 High/Late Medieval Human Isotope Results by Pre- or Post-AD 1350

While the previous sections investigated the data by social and demographic factors, these next sections investigate the data temporally. To investigate changes which may be related to the Black Death in 1348-1349, this section analyses a subset of the High/Late Medieval individuals who were dated with sufficient accuracy that they could be categorised as dying either pre- or post-1350 (following Cessford and Alexander in Robb n.d.).

7.7.1 Results: Pre- or Post-1350

The summary statistics for dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ and enamel carbonate $\delta^{13}C$ values are very similar pre- and post-1350 (Table 40 to Table 42), although the plots show some changes in the range and density of the data (Figure 83 to Figure 87). For example, the mean rib collagen $\delta^{15}N$ values are identical by pre/post-1350 and the $\delta^{15}N$ range is similar in both groups, but the $\delta^{13}C$ range is larger pre-1350 (Table 41, Figure 85). This is illustrated in Figure 86, which displays a 'shrinking' in the inner and outer bag in the post-1350 group, reflecting a smaller range, particularly of the lower $\delta^{13}C$ values. Conversely, the distribution of the enamel carbonate $\delta^{13}C$ data is broadly similar pre- and post-1350, with several low-value outliers (Figure 87).

Enamel carbonate $\delta^{18}O$ values do appear to show a difference pre/post-1350, with the mean $\delta^{18}O$ increasing from -5.1‰ pre-1350 to -4.7‰ post-1350 and the range reduces from 5.0‰ to 4.0‰. (Table 43). The distribution of the data is different, with the pre-1350 values forming a larger, tighter probability density around the median (Figure 88). The pre-1350 group also has high and low-value outliers, whereas the post-1350 group has none. The summary statistics for enamel $^{87}Sr/^{86}Sr$ values by pre/post-1350 show little difference (Table 44) but there may be some difference in the distribution of the data, with the pre-1350 data being more skewed to the lower values (Figure 89). Both groups have two outliers. Plotting the enamel carbonate $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values together shows the general shape of the outer bag is similar pre- and post-1350, although the shape of the inner bags is slightly different, with the post-1350 group having some lower $\delta^{18}O$ values (Figure 90).

Pre- or Post-1350?	***n***	**Dentine $\delta^{13}C$ (‰) (VPDB)**						**Dentine $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Pre-1350	49	-19.3	0.4	-19.3	-20.0	-18.4	1.6	12.0	1.2	12.2	9.3	15.4	6.1
Post-1350	47	-19.1	0.5	-19.1	-20.2	-18.1	2.1	12.0	1.4	12.0	9.1	14.3	5.2
TOTAL	**96**												

Table 40: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by pre/post-1350

Pre- or post-1350?	***n***	**Rib $\delta^{13}C$ (‰) (VPDB)**						**Rib $\delta^{15}N$ (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Pre-1350	91	-19.0	0.5	-19.0	-20.2	-17.5	2.7	12.7	1.1	12.6	10.2	14.9	4.7
Post-1350	49	-18.9	0.3	-18.9	-19.7	-18.3	1.4	12.7	1.2	12.8	9.7	14.6	4.9
TOTAL	**140**												

Table 41: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by pre/post-1350

Pre- or Post-1350?	***n***	**Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Pre-1350	65	-12.8	0.5	-12.8	-14.5	-11.7	-2.8
Post-1350	57	-12.9	0.6	-12.7	-15.1	-11.9	-3.2
TOTAL	**122**						

Table 42: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for High/Late Medieval Cambridgeshire individuals, by pre/post-1350

Pre- or Post-1350?	***n***	**Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)**						***Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)***					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Pre-1350	65	-5.1	0.9	-5.1	-7.4	-2.4	5.0	16.8	1.0	16.8	14.3	19.6	5.3
Post-1350	57	-4.7	0.9	-4.8	-6.9	-2.9	4.0	17.2	1.0	17.2	14.9	19.1	4.2
TOTAL	**122**												

Table 43: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval Cambridgeshire individuals, by pre/post-1350

Pre- or Post-1350?	***n***	**Enamel $^{87}Sr/^{86}Sr$**						**Sr ppm**	
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Pre-1350	37	0.7090	0.0008	0.7087	0.7082	0.7122	0.0040	127	43
Post-1350	41	0.7091	0.0006	0.7091	0.7084	0.7115	0.0031	122	44
TOTAL	**78**								

Table 44: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals, by pre/post-1350

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

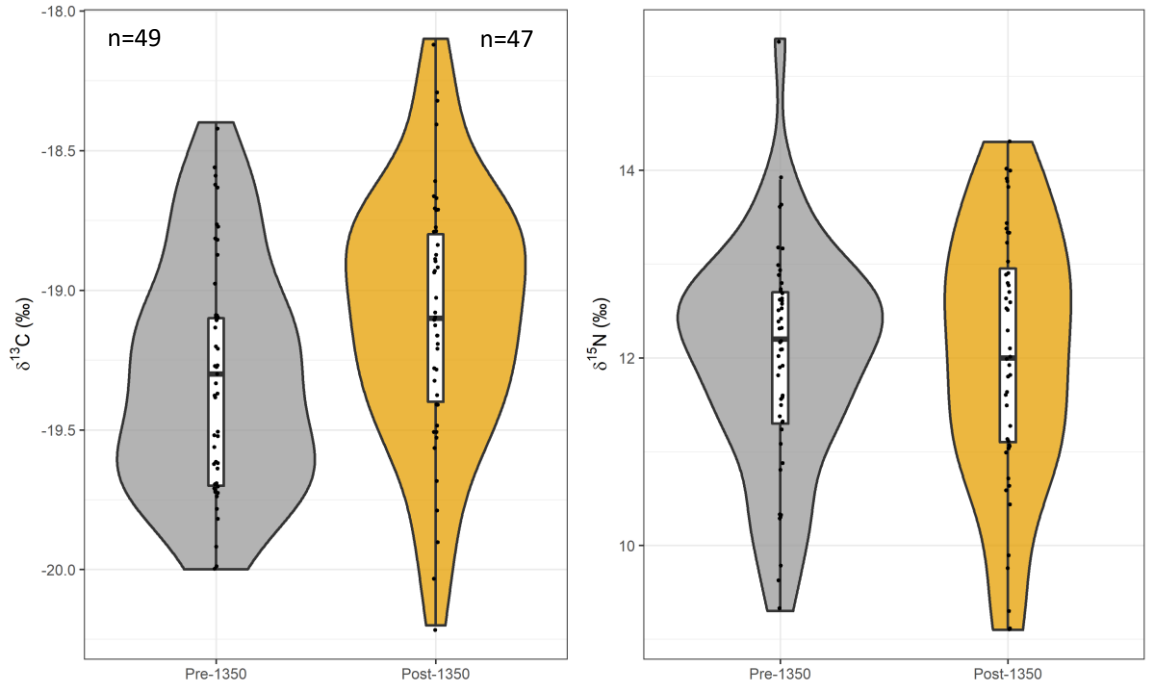


Figure 83: Violinplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

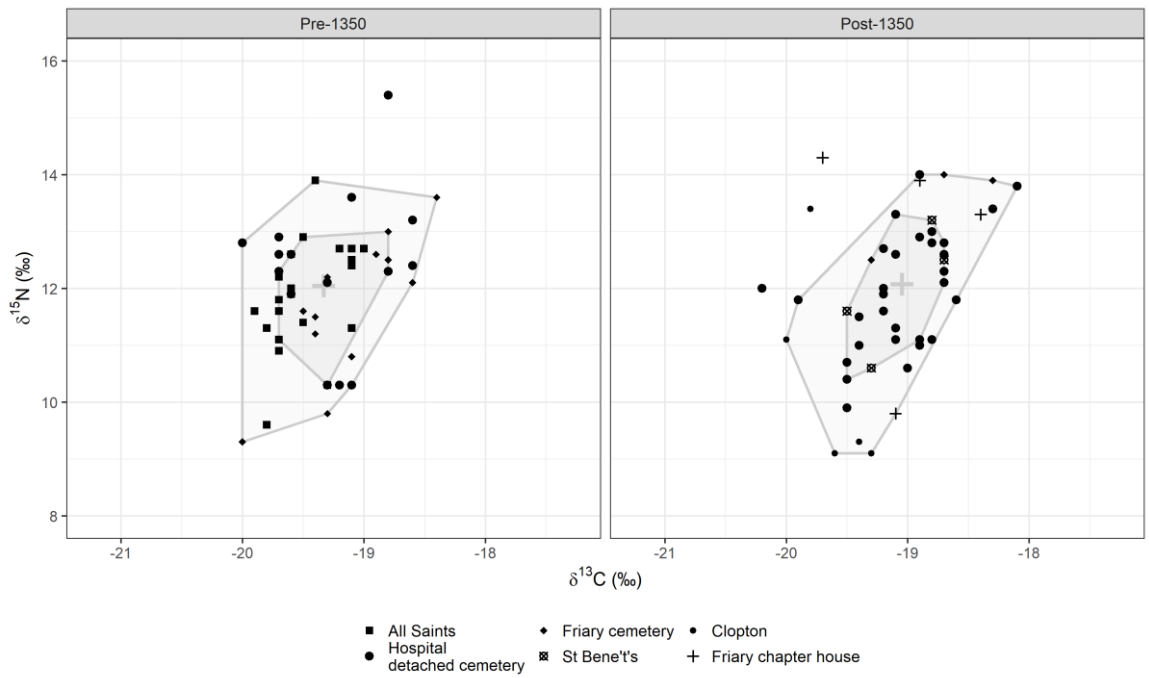


Figure 84: Bagplots with scatterplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

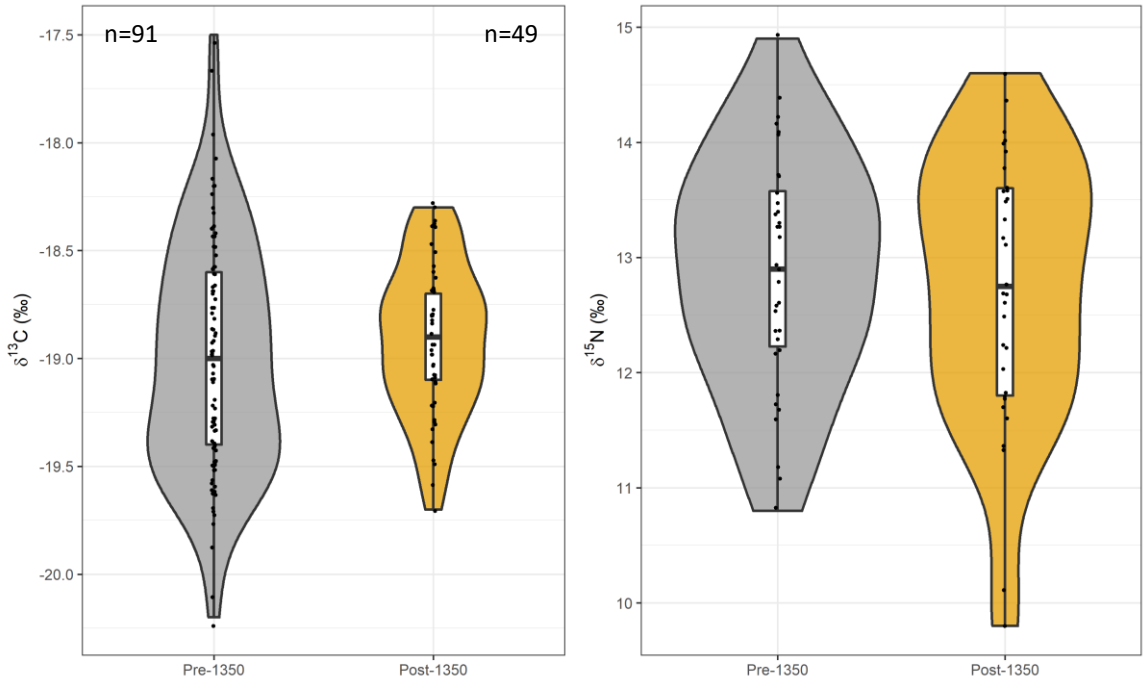


Figure 85: Violinplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

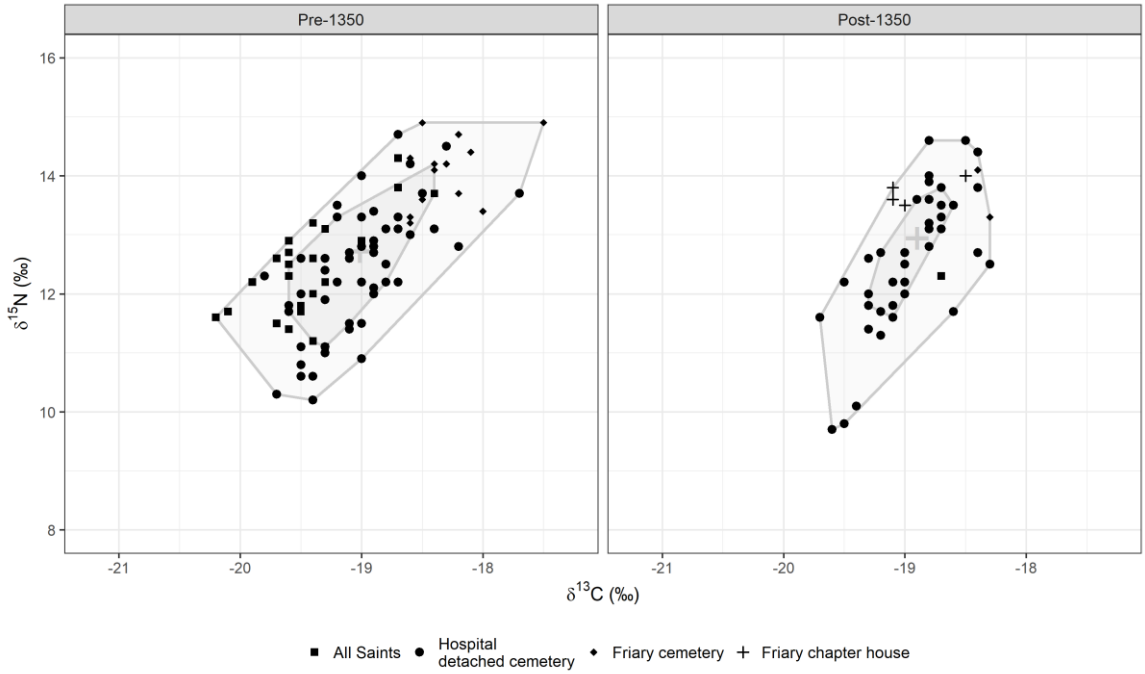


Figure 86: Bagplots with scatterplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

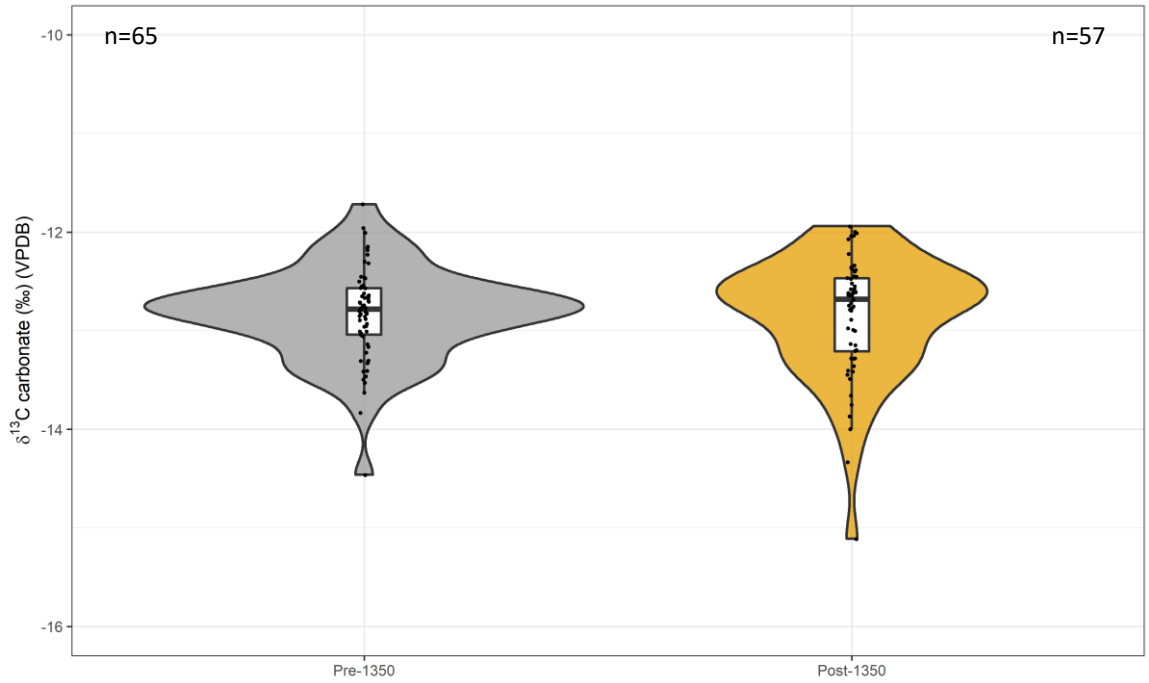


Figure 87: Violinplots showing tooth enamel carbonate $\delta^{13}C$ values for all High/Late Medieval Cambridgeshire individuals who were assigned a pre or post AD 1350 date

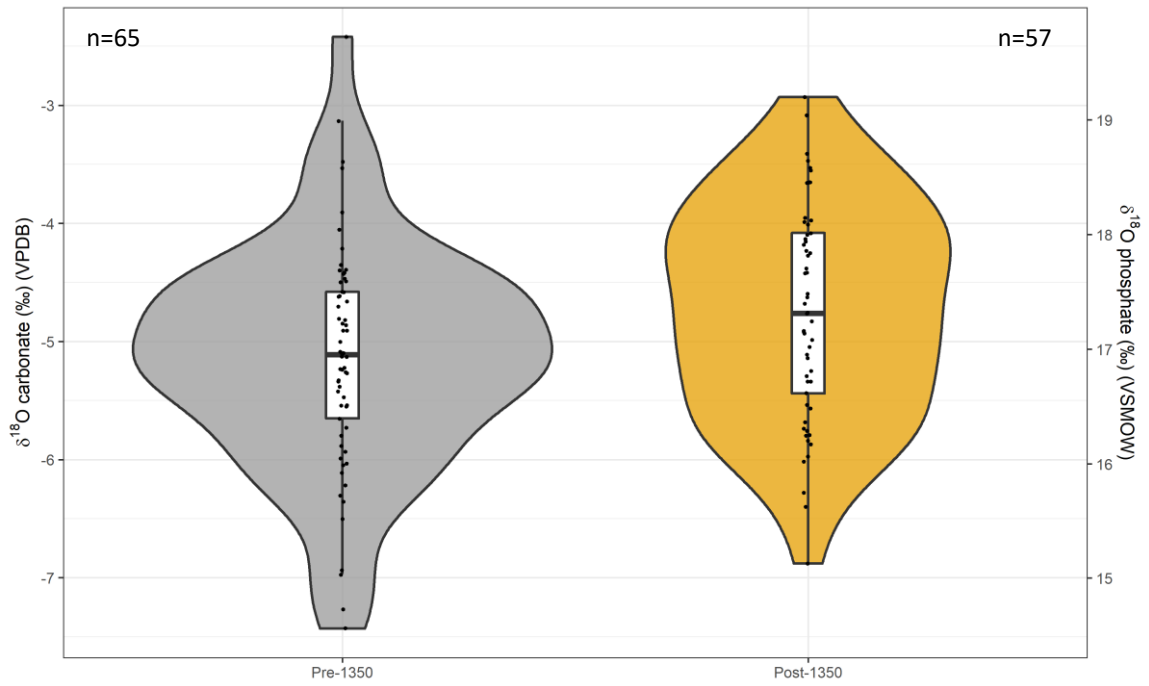


Figure 88: Violinplot showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

Enamel $^{87}Sr/^{86}Sr$

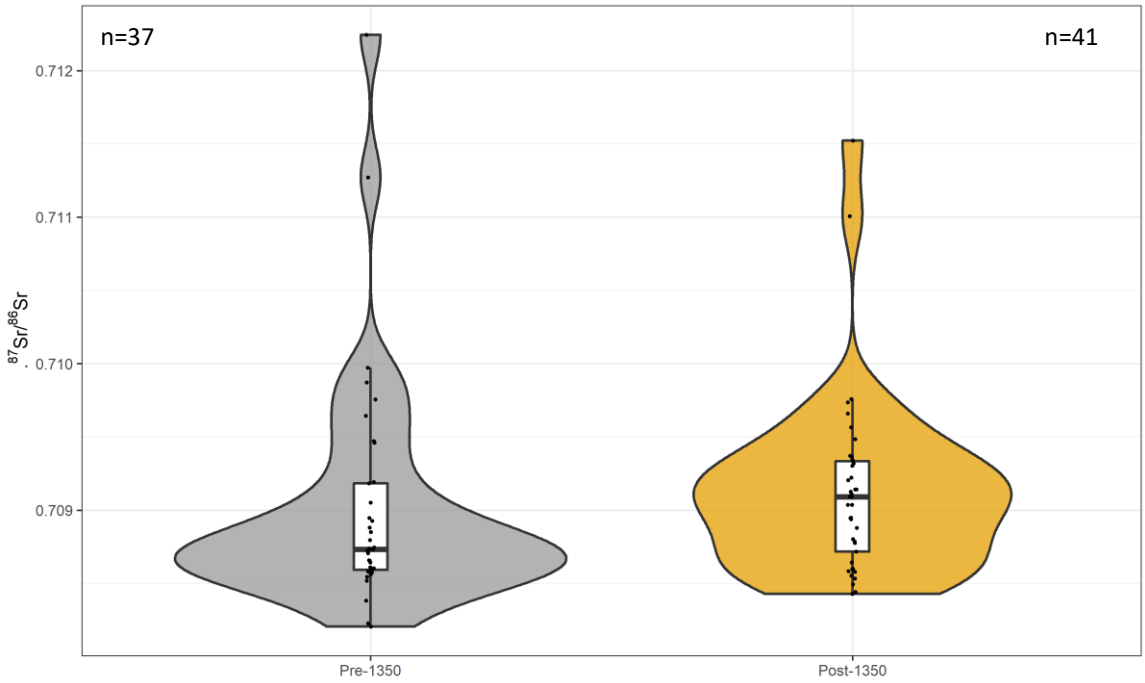


Figure 89: Violinplot showing tooth enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

Enamel Carbonate $\delta^{18}O$ and Enamel $^{87}Sr/^{86}Sr$

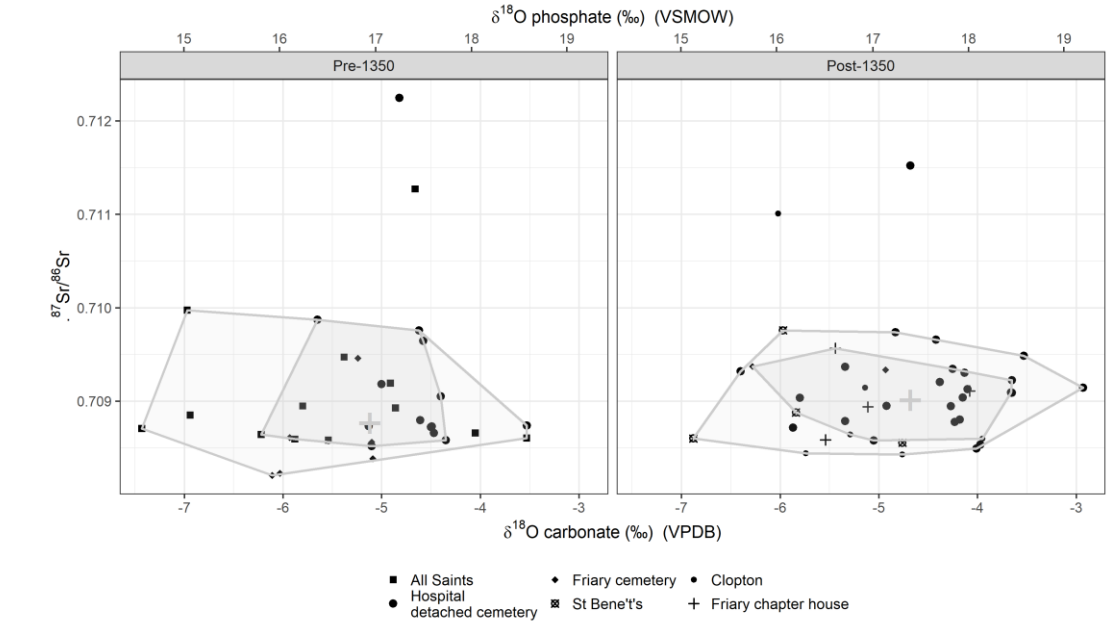


Figure 90: Bagplots showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) and enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date

7.7.2 Results: Pre- or Post-1350 and Site Subgroup (and Sex)

Combining several site subgroups into pre- and post-1350 groups may mask more nuanced changes, so this section looks more closely at the site subgroups. There are only two site subgroups with enough isotope data pre-and post-1350 to make comparisons – the Hospital detached cemetery and the Friary cemetery, so the discussion will focus on these sites, although pre/post-1350 data from other High/Late Medieval sites is shown on the plots for context.

The individuals from Hospital detached cemetery show some differences in their dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values but the enamel carbonate $\delta^{13}C$ data is very similar pre/post-1350 (Table 45, Table 46). The difference in mean dentine $\delta^{15}N$ values is 0.3‰, but when further broken down by sex, there is a larger difference between pre- and post-1350 male mean $\delta^{15}N$ values than female (male pre-1350= 12.8‰, male post-1350= 11.8‰) (Table 45, Figure 91). For rib collagen, females show a 0.6‰ increase, whereas males show a 0.2‰ decrease in $\delta^{15}N$ values post-1350 (Table 46, Figure 92). Figure 93 shows pre/post-1350 Hospital female and male dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values overlain to demonstrate differences between tissues between sexes, by time period. Both show changes in the shape of the data post-1350, but the change is more dramatic in females.

The Friary cemetery data shows a relatively large increase in mean dentine collagen $\delta^{15}N$ values (pre-1350: 11.8‰, post-1350: 13.5‰) (Table 45, Figure 91). Rib collagen mean $\delta^{13}C$ values remain similar, but there is a 0.4‰ decrease in the mean $\delta^{15}N$ values post-1350 (Table 46). However, the difference in $\delta^{13}C$ and $\delta^{15}N$ values is largely due to two post-1350 outliers and the small sample size of the post-1350 group (n=3). There is a 0.4‰ increase in the mean enamel carbonate $\delta^{13}C$ values at the Friary post-1350 (Table 47, Figure 94).

There are differences in the probability densities in $\delta^{13}C$ and $\delta^{15}N$ values pre/post-1350 at both the Friary and Hospital cemeteries, however, Figure 91 and Figure 92 highlight that while there are pre/post-1350 intra-site differences, these are still smaller than some of the inter-site differences shown, particularly in the sites with post-1350 values.

There are very little intra-site differences in mean pre- and post-1350 $\delta^{18}O$ values (Table 48), although when further broken down by sex, there appears to be a larger difference at the Hospital between female and male mean $\delta^{18}O$ values in the pre-1350 group than the post-1350

group, and the females show an increase in $\delta^{18}O$ values of 0.4‰ post-1350. There is a 0.5‰ increase in median $\delta^{18}O$ values post-1350 at the Hospital and this can be seen in the divergence of the boxplots and probability densities in Figure 95. The mean $^{87}Sr/^{86}Sr$ values at the Hospital are identical for both periods and the median increases by 0.0003 post-1350 (Table 49, Figure 96). However, there may be a difference in the distribution of the data, with the pre-1350 group showing much more clustering. The difference between median values for males and females at the Hospital remains similar in both periods.

Site Subgroup	Pre- or Post-1350?	Sex	n	Dentine δ13C (‰) (VPDB)						Dentine δ15N (‰) (AIR)					
				Mean	SD	Median	Min	Max	Range	Mean	SD	Median	Min	Max	Range
Hospital detached cemetery	Pre	**ALL**	15	-19.3	0.4	-19.3	-20.0	-18.6	1.4	12.3	1.3	12.4	10.3	15.4	5.1
		Female	10	-19.3	0.4	-19.2	-20.0	-18.6	1.4	12.1	1.1	12.3	10.3	13.6	3.3
		Male	5	-19.2	0.5	-19.3	-19.7	-18.6	1.1	12.8	1.8	12.6	10.3	15.4	5.1
	Post	**ALL**	30	-19.0	0.4	-19.1	-20.2	-18.1	2.1	12.0	1.0	11.9	9.9	14.0	4.1
		Female	10	-19.1	0.6	-19.1	-20.2	-18.1	2.1	12.3	1.0	12.2	10.7	13.8	3.1
		Male	20	-19.0	0.3	-18.9	-19.9	-18.6	1.3	11.8	1.0	11.8	9.9	14.0	4.1
Friary cemetery	Pre	**ALL**	13	-19.1	0.5	-19.1	-20.0	-18.4	1.6	11.8	1.3	12.1	9.3	13.6	4.3
		Male	10	-19.0	0.4	-19.0	-19.5	-18.4	1.1	12.1	0.9	12.1	10.8	13.6	2.8
	Post	**ALL**	3	-18.8	0.5	-18.7	-19.3	-18.3	1.0	13.5	0.8	13.9	12.5	14.0	1.5
		Male	3	-18.8	0.5	-18.7	-19.3	-18.3	1.0	13.5	0.8	13.9	12.5	14.0	1.5

Table 45: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval individuals from the Hospital detached cemetery and Friary cemetery only, by pre/post-1350 and sex (adults only)

Site Subgroup	Pre- or Post-1350?	Sex	n	Rib δ13C (‰) (VPDB)						Rib δ15N (‰) (AIR)					
				Mean	SD	Median	Min	Max	Range	Mean	SD	Median	Min	Max	Range
Hospital detached cemetery	Pre	**ALL**	52	-19.0	0.4	-19.0	-19.8	-17.7	2.1	12.4	1.1	12.4	10.2	14.7	4.5
		Female	24	-19.2	0.4	-19.1	-19.8	-18.2	1.6	12.1	0.9	12.2	10.3	14.0	3.7
		Male	23	-18.9	0.4	-18.9	-19.5	-17.7	1.8	12.7	1.2	13.0	10.6	14.7	4.1
	Post	**ALL**	41	-18.9	0.3	-18.9	-19.7	-18.3	1.4	12.6	1.2	12.7	9.7	14.6	4.9
		Female	12	-19.0	0.3	-18.9	-19.7	-18.6	1.1	12.7	0.9	12.7	11.6	14.6	3.0
		Male	28	-19.0	0.4	-18.9	-19.6	-18.3	1.3	12.5	1.3	12.6	9.7	14.6	4.9
Friary cemetery	Pre	**ALL**	16	-18.3	0.3	-18.4	-18.6	-17.5	1.1	14.1	0.5	14.1	13.2	14.9	1.7
		Male	16	-18.3	0.3	-18.4	-18.6	-17.5	1.1	14.1	0.5	14.1	13.2	14.9	1.7
	Post	**ALL**	3	-18.5	0.3	-18.4	-18.9	-18.3	0.6	13.7	0.4	13.6	13.3	14.1	0.8
		Male	3	-18.5	0.3	-18.4	-18.9	-18.3	0.6	13.7	0.4	13.6	13.3	14.1	0.8

Table 46: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval individuals from the Hospital detached cemetery and Friary cemetery only, by pre/post-1350 and sex (adults only)

Site Subgroup	*Pre- or Post-1350?*	*Sex*	*n*	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	Pre	**ALL**	28	-12.7	0.4	-12.7	-13.6	-11.7	1.9
		Female	12	-12.8	0.4	-12.8	-13.3	-11.7	1.6
		Male	10	-12.7	0.5	-12.7	-13.6	-12.0	1.6
	Post	**ALL**	40	-12.7	0.6	-12.6	-15.1	-11.9	3.2
		Female	10	-12.8	0.9	-12.5	-15.1	-12.0	3.1
		Male	21	-12.7	0.5	-12.6	-13.7	-12.0	1.7
Friary cemetery	Pre	**ALL**	14	-12.9	0.3	-12.8	-13.5	-12.5	1.0
		Male	11	-12.8	0.2	-12.8	-13.0	-12.5	0.5
	Post	**ALL**	3	-12.5	0.2	-12.6	-12.7	-12.2	0.5
		Male	3	-12.5	0.2	-12.6	-12.7	-12.2	0.5

Table 47: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for High/Late Medieval individuals from the Hospital detached cemetery and Friary cemetery only, by pre/post-1350 and sex (adults only)

Site Subgroup	*Pre- or Post-1350?*	*Sex*	*n*	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						*Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)*					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	Pre	**ALL**	28	-4.7	0.8	-4.8	-6.0	-2.4	3.6	17.2	0.8	17.2	15.8	19.6	3.8
		Female	12	-4.8	0.7	-4.9	-5.7	-3.1	2.6	17.1	0.7	17.0	16.2	18.9	2.7
		Male	10	-4.3	0.9	-4.5	-6.0	-2.4	3.6	17.6	1.0	17.4	15.8	19.6	3.8
	Post	**ALL**	40	-4.5	0.8	-4.3	-6.4	-2.9	3.5	17.5	0.9	17.6	15.4	19.1	3.7
		Female	10	-4.4	0.9	-4.3	-5.8	-2.9	2.9	17.5	0.9	17.6	16.0	19.1	3.1
		Male	21	-4.4	0.8	-4.2	-6.4	-3.1	3.3	17.5	0.8	17.7	15.4	18.9	3.5
Friary cemetery	Pre	**ALL**	14	-5.5	0.6	-5.4	-6.5	-4.2	2.3	16.3	0.7	16.4	15.3	17.7	2.4
		Male	11	-5.6	0.5	-5.5	-6.5	-5.1	1.4	16.2	0.5	16.3	15.3	16.8	1.5
	Post	**ALL**	3	-5.6	0.7	-5.7	-6.3	-4.9	1.4	16.2	0.7	16.2	15.5	17.0	17.1
		Male	3	-5.6	0.7	-5.7	-6.3	-4.9	1.4	16.2	0.7	16.2	15.5	17.0	1.5

Table 48: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval individuals from the Hospital detached cemetery and Friary cemetery only, by pre/post-1350 and sex (adults only)

Site Subgroup	*Pre- or Post-1350?*	*Sex*	*n*	Enamel $^{87}Sr/^{86}Sr$						Sr ppm	
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Hospital detached cemetery	Pre	**ALL**	14	0.7092	0.0010	0.7088	0.7085	0.7122	0.0037	124	32
		Female	7	0.7094	0.0013	0.7088	0.7086	0.7122	0.0036	134	37
		Male	6	0.7091	0.0005	0.7089	0.7087	0.7098	0.0011	121	22
	Post	**ALL**	25	0.7092	0.0006	0.7091	0.7085	0.7115	0.0030	122	35
		Female	9	0.7090	0.0004	0.7090	0.7085	0.7097	0.0012	136	30
		Male	13	0.7093	0.0007	0.7092	0.7085	0.7115	0.0030	119	37
Friary cemetery	Pre	**ALL**	10	0.7086	0.0004	0.7086	0.7082	0.7095	0.0013	106	52
		Male	8	0.7086	0.0004	0.7086	0.7082	0.7095	0.0013	111	55
	Post	**ALL**	2	0.7094	0.0000	0.7094	0.7093	0.7094	0.0001	149	18
		Male	2	0.7094	0.0000	0.7094	0.7093	0.7094	0.0001	149	18

Table 49: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval individuals from the Hospital detached cemetery and Friary cemetery only, by pre/post-1350 and sex (adults only)

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

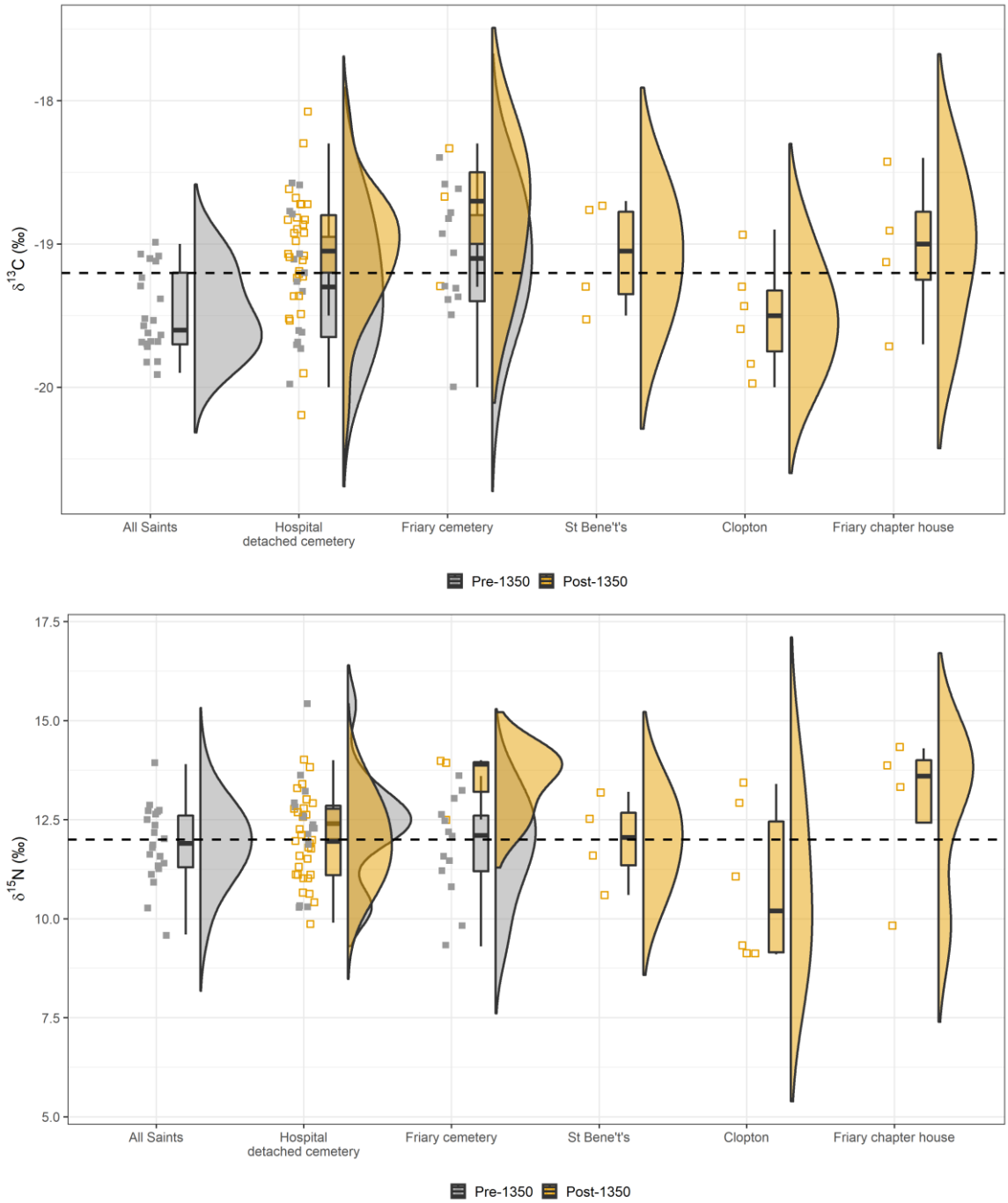


Figure 91: Raincloud plots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

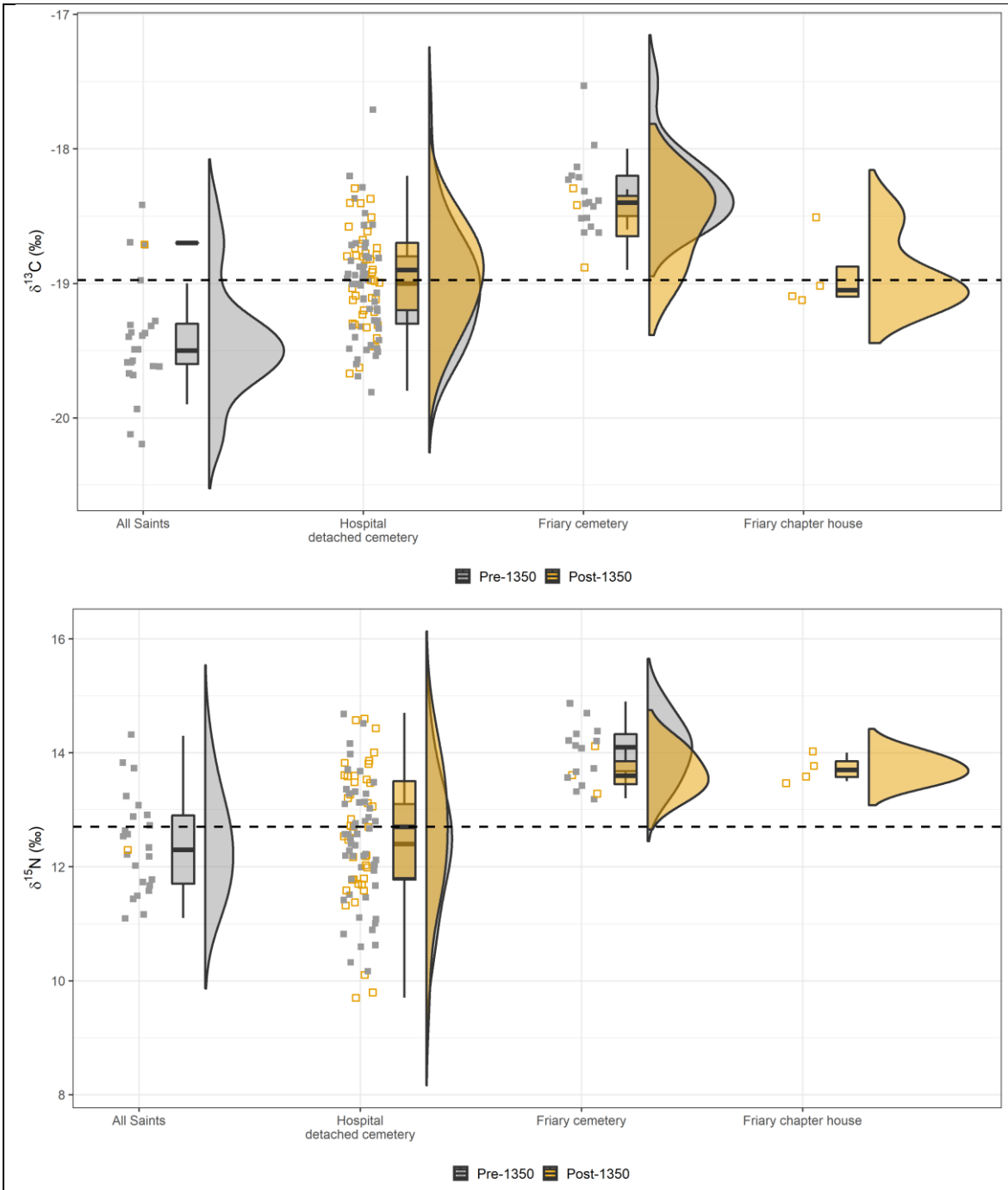


Figure 92: Raincloud plots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

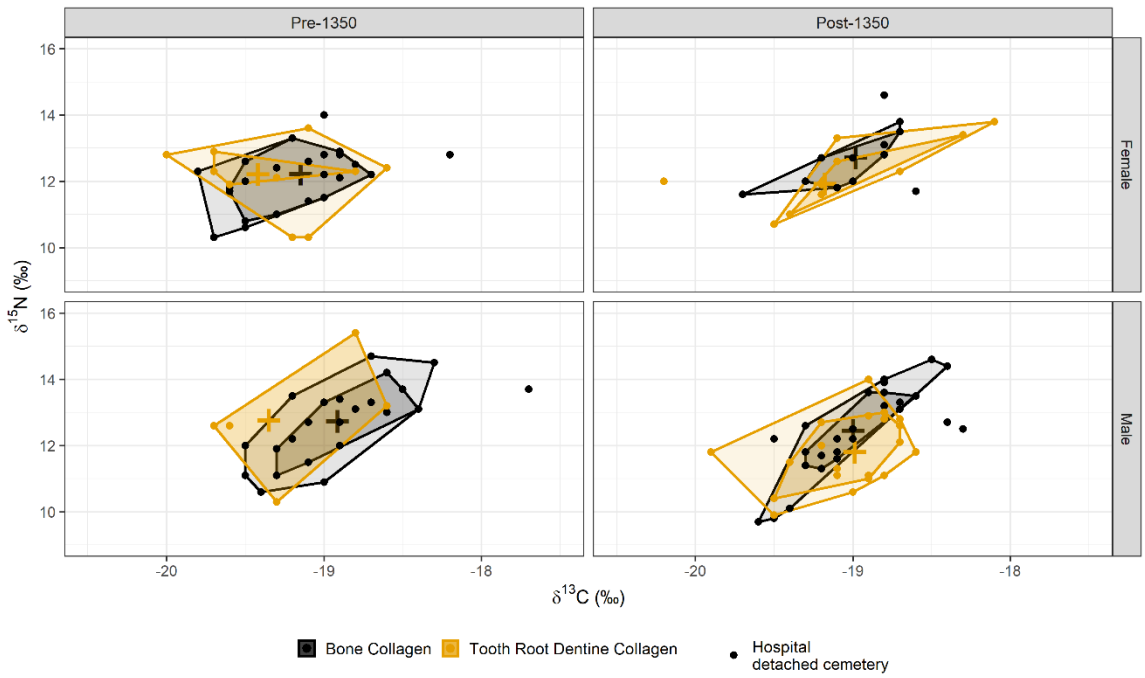


Figure 93: Bagplots with scatterplots showing dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult individuals from the Hospital detached cemetery who were assigned a pre- or post-1350 date and were assigned a female/ male sex estimate (faceted by date and sex)

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

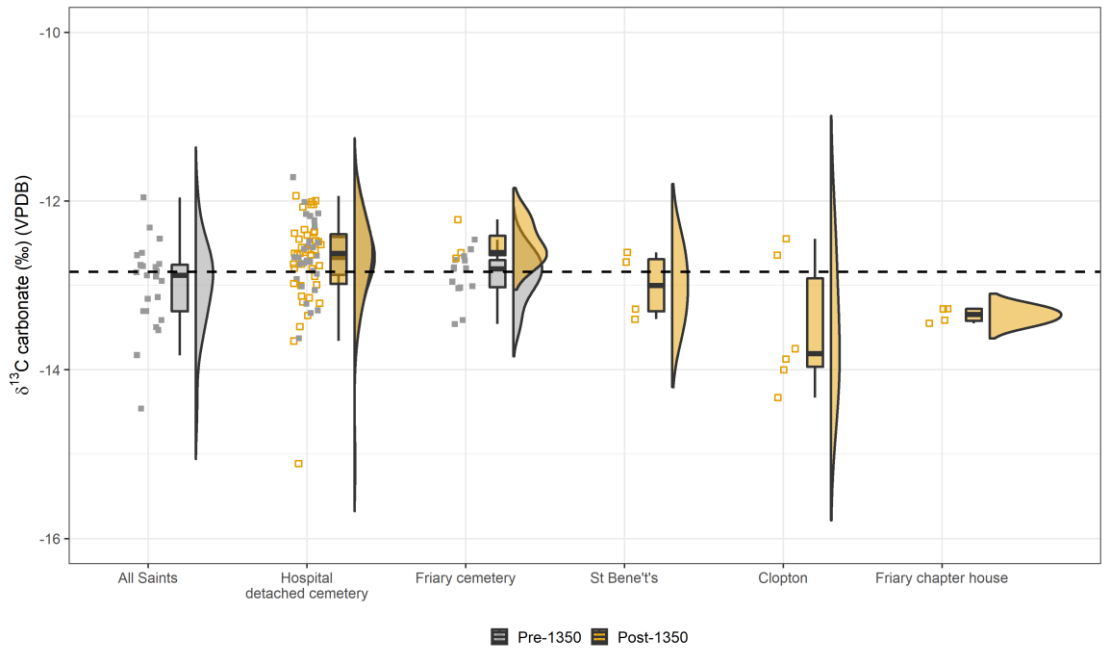


Figure 94: Raincloud plot showing tooth enamel carbonate $\delta^{13}C$ values for all High/Late Medieval Cambridgeshire individuals who were assigned a pre- or post-1350 date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in the plot

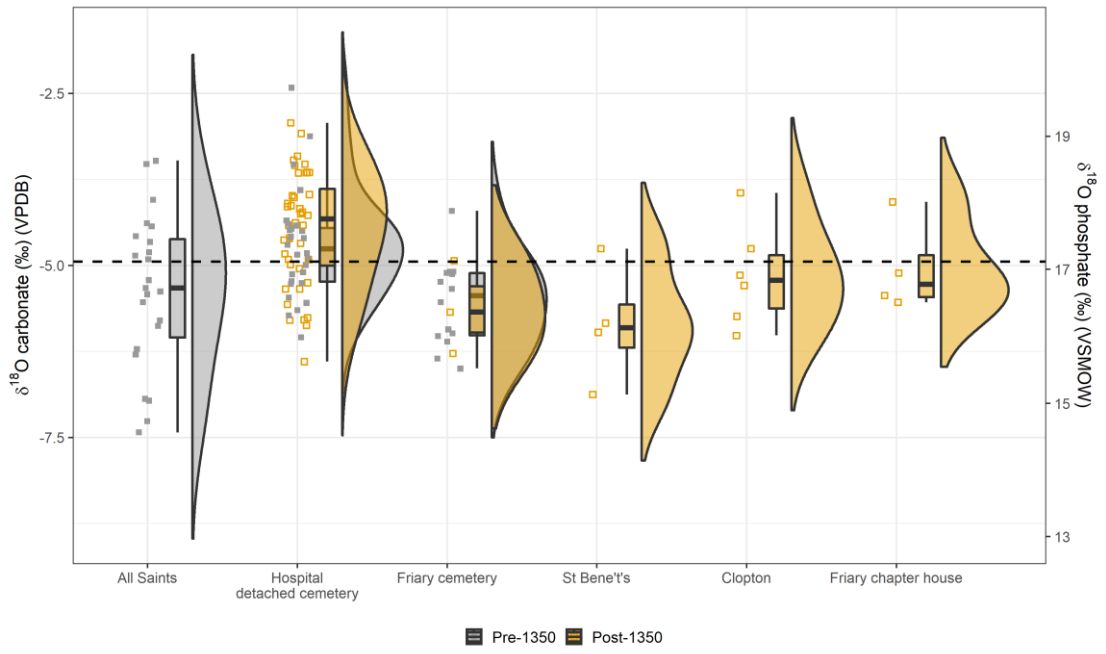


Figure 95: Raincloud plots showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval individuals who were assigned a pre- or post-1350 date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot

Enamel $^{87}Sr/^{86}Sr$

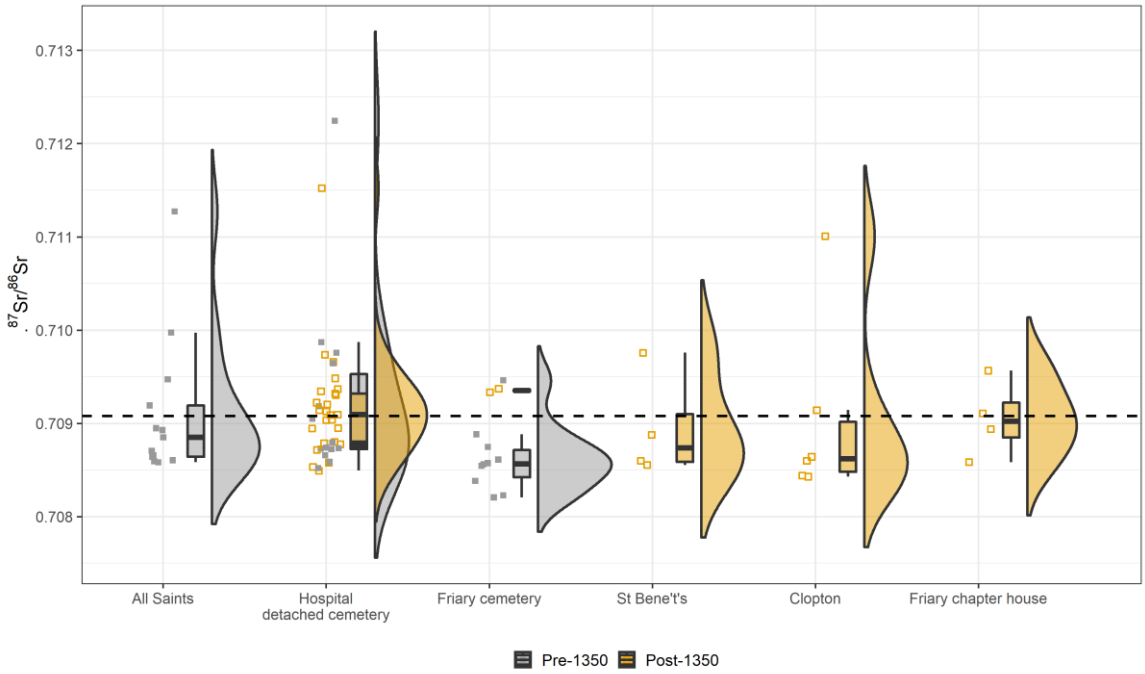


Figure 96: Raincloud plots showing tooth enamel carbonate $^{87}Sr/^{86}Sr$ values for High/Late Medieval individuals who were assigned a pre- or post-1350 date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot

7.7.3 Statistical Testing: Pre- or Post-1350

Comparisons of the High/Late Medieval isotope data by pre- or post-1350 show that dentine collagen $\delta^{13}C$ values and enamel carbonate $\delta^{18}O$ values are unlikely to have come from populations with equal means (Welch's t-tests: dentine $\delta^{13}C$: p=0.0123; enamel carbonate $\delta^{18}O$: p=0.0239). However, comparisons of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ values by pre/post-1350 at the Hospital detached cemetery only showed no difference between the means, indicating that any differences seen in the overall data is likely to be a result of comparing different sites rather than temporal change.

Comparisons of the High/Late Medieval isotope data by pre- or post-1350 and sex show that the rib collagen $\delta^{13}C$ and $\delta^{15}N$ values are unlikely to come from populations with the same distribution (Kruskal-Wallis tests: $\delta^{13}C$: p=0.0001; $\delta^{15}N$: p=0.0004). Post-hoc tests show that the rib collagen $\delta^{13}C$ data distribution is different between pre-1350 adult females and pre-1350 males (rib $\delta^{13}C$: $p.adj$=<0.0001) as well as between pre-1350 females and post-1350 males($p.adj$=0.0026). A difference between the adult rib collagen $\delta^{15}N$ distribution is also present between pre-1350 females and males (rib $\delta^{15}N$: $p.adj$=0.0016). This means there is a difference in both rib $\delta^{13}C$ and $\delta^{15}N$ values between females and males in the pre-1350 period which is not detectable in the post-1350 period, which could indicate less diversity in diets or more access to similar food sources in the later period.

However, statistical comparisons of the isotope data by - or post-1350 or by pre- or post-1350 and sex at the Hospital detached cemetery only indicate no differences between the groupings for any isotope (Appendix VI). This implies the differences seen in the overall data are not necessarily temporal.

7.7.4 Summary: Pre- or Post-1350

The results of this section are inconclusive. There does not appear to be a meaningful difference in dentine or rib $\delta^{15}N$ isotope data pre- or post-1350, but there is a difference in dentine collagen $\delta^{13}C$, which may indicate differences in childhood diet pre- and post-1350 (Richards *et al.* 2002, Burt 2015). When considered by sex, there are differences in adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ values in the pre-1350 group that are not present in the post-1350 group, which could indicate a more homogenised diet in the later period, with more equal

access to food sources. The data appears to show meaningful differences in enamel carbonate $\delta^{18}O$ values between the pre- and post-1350 periods. The post-1350 group has a different distribution, a smaller range, and a lack of outliers. Statistical testing also indicates differences in the mean between the two periods. However, the $^{87}Sr/^{86}Sr$ data does not show a dramatic change between the pre- and post-1350 groups – there are only two outliers in each period, demonstrating there is no detectable increase in 'non-locals' post-1350.

The major weakness of the overall pre/post-1350 analysis in this section is that only two sites have data that span both periods and therefore many of the individuals in the pre-1350 group are from different sites to the post-1350 group. Since previous sections have demonstrated that the sites have distinctive isotopic signatures, then this pooled data is likely to be unrepresentative. Therefore, analysis of pre- and post-1350 data on a site-by-site basis is more likely to yield useful comparisons. At the Hospital detached cemetery, there is some indication of differences in the distribution of the dentine collagen isotope values pre- and post-1350 but overall, statistical testing showed no meaningful difference in the means of the $\delta^{13}C$ and $\delta^{15}N$ or $\delta^{18}O$ values in the pre- and post-1350 groups. The $^{87}Sr/^{86}Sr$ data may show some difference in pre- and post-1350 values at the Hospital. The distribution of the scatter points for the pre-1350 groups appear to be more clustered and post-1350 appear more dispersed, although all are within the 'local' range. This could indicate a change in admittance into the Hospital, with an increased catchment area post-1350. The isotope values from the Hospital suggest that if the plague had any impact upon the diet of the Medieval population of Cambridge, it was either not experienced at the Hospital, perhaps due to more robust food supply routes, an institutionalised diet and its recruitment practices (Rubin 1987, Woolgar 2006b) (see Sections 2.3.2 and 4.5.2.2), or it is undetectable to isotope analysis. There may, however, be subtle changes in mobility post-1350, although still within the local area (Evans, Chenery, *et al.* 2018).

7.8 High/Late Medieval Human Isotope Results by Medieval Century

To further investigate temporal changes, this section investigates the data by Medieval century using a subset of the High/Late Medieval individuals who could be categorised by whether they were likely to have died in the 13th, 14th or 15th century (following Cessford and Alexander in Robb n.d.). However, the data is predominantly from the 14th century and this results in unequal sample sizes across the centuries, which should be considered.

7.8.1 Results: Medieval Century

The dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values appear to show some differences by century (Table 50, Table 51, Figure 97 to Figure 100). In general, the mean dentine and rib $\delta^{13}C$ values are similar by century but the mean dentine $\delta^{15}N$ values change through time, from 13.0‰ in the 13th century, to 11.8‰ in the 14th, to 12.5‰ in the 15th century. The median and range are also similarly varied, with the largest $\delta^{15}N$ range in the 14th century although the sample size is much larger for the 14th century. The mean rib $\delta^{15}N$ values increase through time, from 12.5‰ in the 13th century, to 12.9‰ in the 14th century, to 13.0‰ in the 15th century. The range and distribution of the rib data appears to change by century, showing a smaller range and generally higher $\delta^{15}N$ values in the 15th century, but this could be a product of the smaller sample size (Figure 99). It is difficult to identify definite trends with the uneven sample sizes, but there does appear to be larger differences between the centuries in dentine than rib collagen values, which could mean that childhood diet underwent more changes (Sealy *et al.* 1995). The enamel carbonate $\delta^{13}C$ values are very similar by century, with no real biologically meaningful change through time, although the range is larger in the 14th century (Table 52). The distribution of the data looks quite different by century in Figure 101, with the 13th century showing a well-distributed curve and the 14th century showing a more 'stingray-like' distribution, although, again, this is likely due to the differences in sample size. The 14th century group does have a low-value outlier.

The enamel carbonate $\delta^{18}O$ values show some changes by century, with the lowest mean and median $\delta^{18}O$ values occurring in the 14th century and the highest occurring in the 15th century (Table 53). Figure 102 illustrates the changes in the median values and shows that the data

density is slightly skewed towards the higher values for each century. Only the 13th-century group has an outlier. The median $^{87}Sr/^{86}Sr$ values for High/Late Medieval individuals increases by century, from 0.7087 in the 13th to 0.7092 in the 15th century (Table 54). The range is largest in the 14th century, caused by a high-value outlier. The distribution of the data looks quite different by century in Figure 103, but this is probably largely due to very different sample sizes, although there are no outliers in the 15th-century group, despite not being the smallest sample. Combining the enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ in Figure 104 further confirms that the range of the majority of the values is similar through time, with some high-value outliers in the 13th and 14th centuries.

Medieval Century	*n*	Dentine $\delta^{13}C$ (‰) (VPDB)						Dentine $\delta^{15}N$ (‰) (AIR)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
13th	9	-19.3	0.4	-19.6	-19.7	-18.6	1.1	13.0	1.1	12.6	11.9	15.4	3.5
14th	51	-19.2	0.5	-19.2	-20.2	-18.0	2.2	11.8	1.4	11.9	9.3	15.3	6.0
15th	11	-19.0	0.5	-18.9	-19.9	-18.3	1.6	12.5	1.4	12.8	9.8	14.3	4.5
TOTAL	**71**												

Table 50: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals, by High/Late Medieval century

Medieval Century	*n*	Rib $\delta^{13}C$ (‰) (VPDB)						Rib $\delta^{15}N$ (‰) (AIR)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
13th	38	-19.0	0.4	-19.0	-19.7	-17.7	2.0	12.5	1.0	12.6	10.3	14.7	4.4
14th	67	-18.9	0.5	-18.8	-19.8	-17.5	2.3	12.9	1.3	13.1	9.7	15.2	5.5
15th	15	-18.9	0.3	-18.8	-19.5	-18.3	1.2	13.0	0.9	13.5	11.4	14.0	2.6
TOTAL	**120**												

Table 51: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals, by High/Late Medieval century

Medieval Century	*n*	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
13th	18	-12.6	0.5	-12.6	-13.6	-11.7	-1.9
14th	64	-12.8	0.5	-12.8	-15.1	-11.9	-3.2
15th	14	-12.8	0.4	-12.7	-13.4	-12.0	-1.4
TOTAL	**96**						

Table 52: Summary statistics for tooth enamel carbonate $\delta^{13}C$ for High/Late Medieval Cambridgeshire individuals, by High/Late Medieval century

Medieval Century	*n*	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						*Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)*					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
13th	18	-4.7	0.9	-4.7	-6.0	-2.4	3.6	17.3	1.0	17.3	15.8	19.6	3.8
14th	64	-4.9	0.9	-4.9	-6.9	-2.9	4.0	17.0	0.9	17.0	14.9	19.1	4.2
15th	14	-4.5	0.8	-4.3	-5.9	-3.5	2.4	17.4	0.9	17.7	16.0	18.5	2.5
TOTAL	**96**												

Table 53: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) for High/Late Medieval Cambridgeshire individuals, by High/Late Medieval century

Medieval century	***n***	**Enamel $^{87}Sr/^{86}Sr$**						**Sr ppm**	
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
13th	9	0.7094	0.0012	0.7087	0.7085	0.7122	0.0037	124	38
14th	41	0.7091	0.0009	0.7089	0.7082	0.7134	0.0052	119	38
15th	10	0.7092	0.0004	0.7092	0.7085	0.7097	0.0012	103	28
TOTAL	**60**								

Table 54: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for all High/Late Medieval Cambridgeshire individuals, by High/Late Medieval century

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

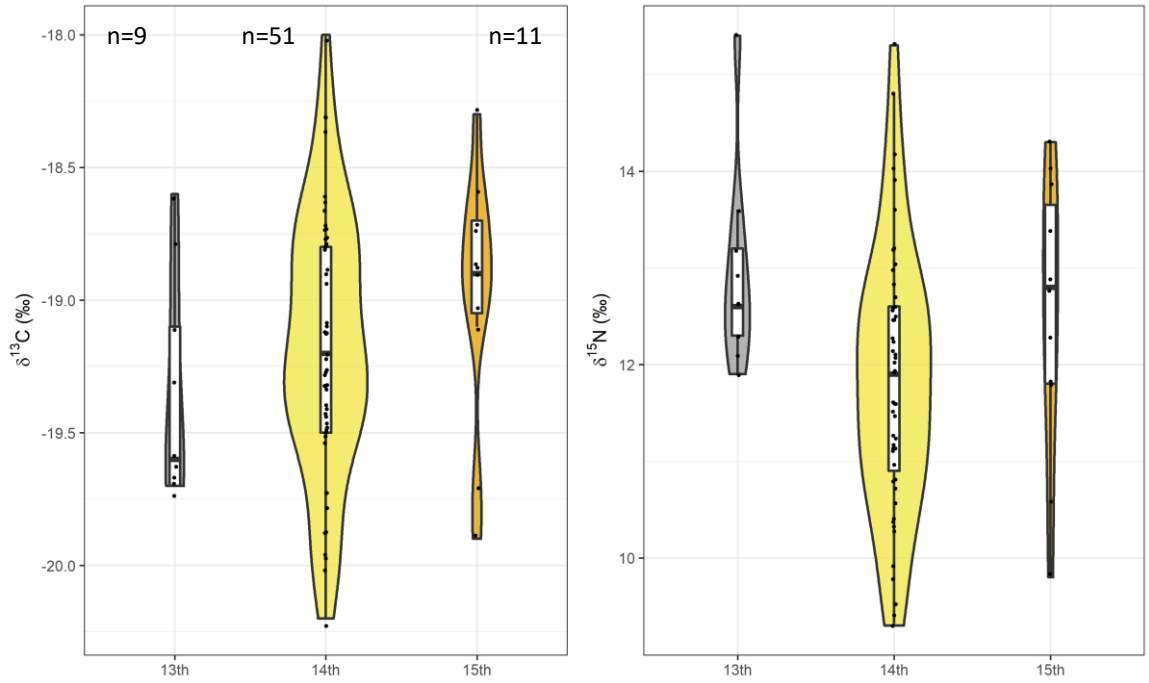


Figure 97: Violinplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

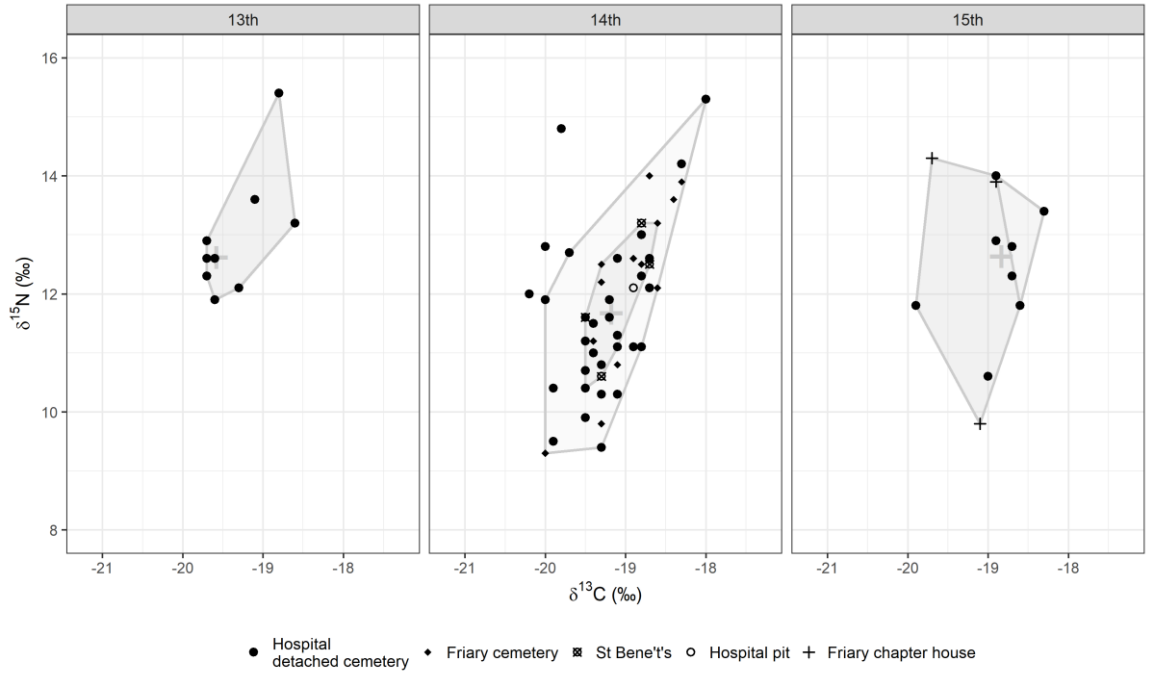


Figure 98: Bagplots with scatterplots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

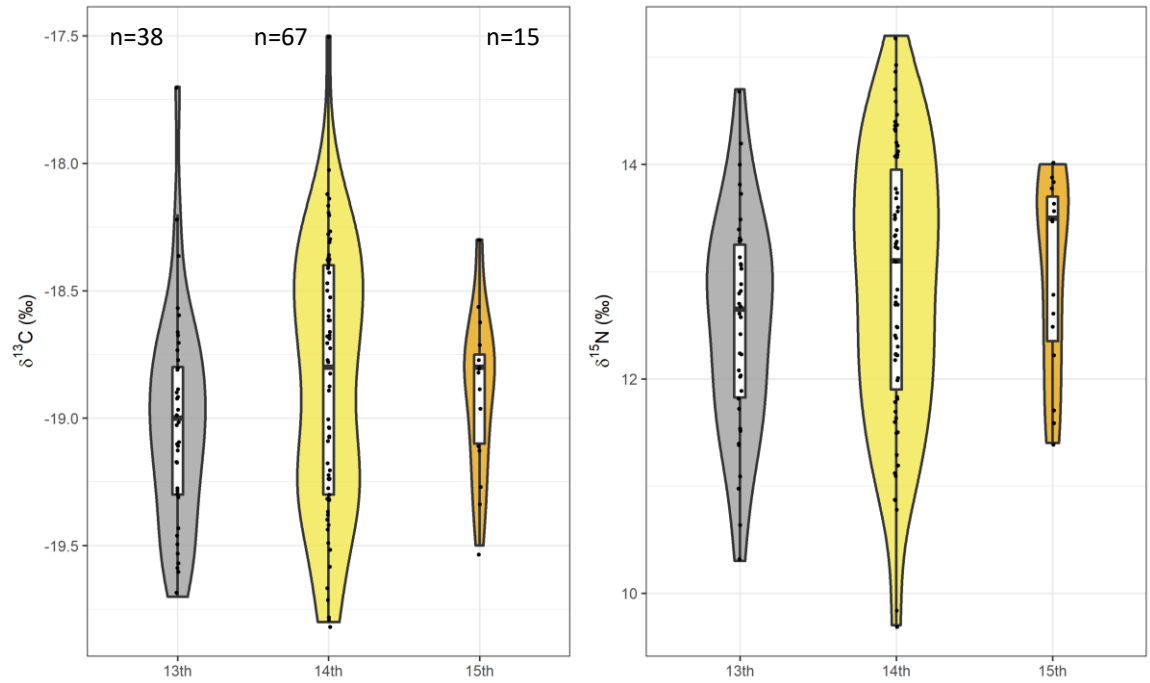


Figure 99: Violinplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

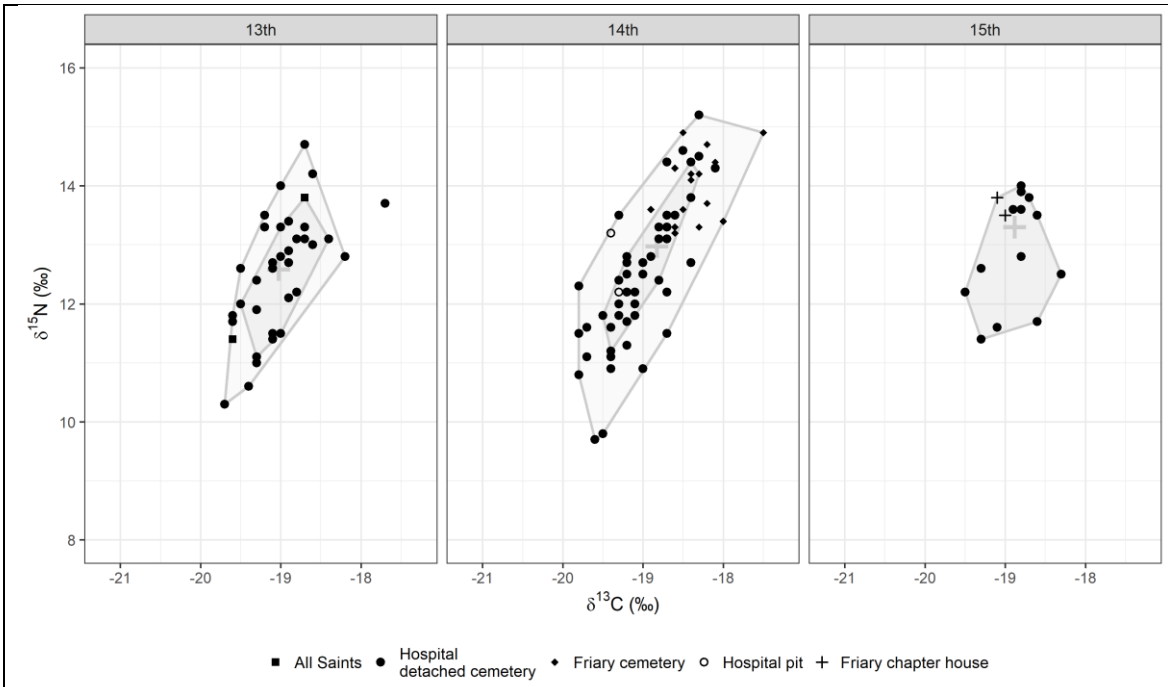


Figure 100: Bagplots with scatterplots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

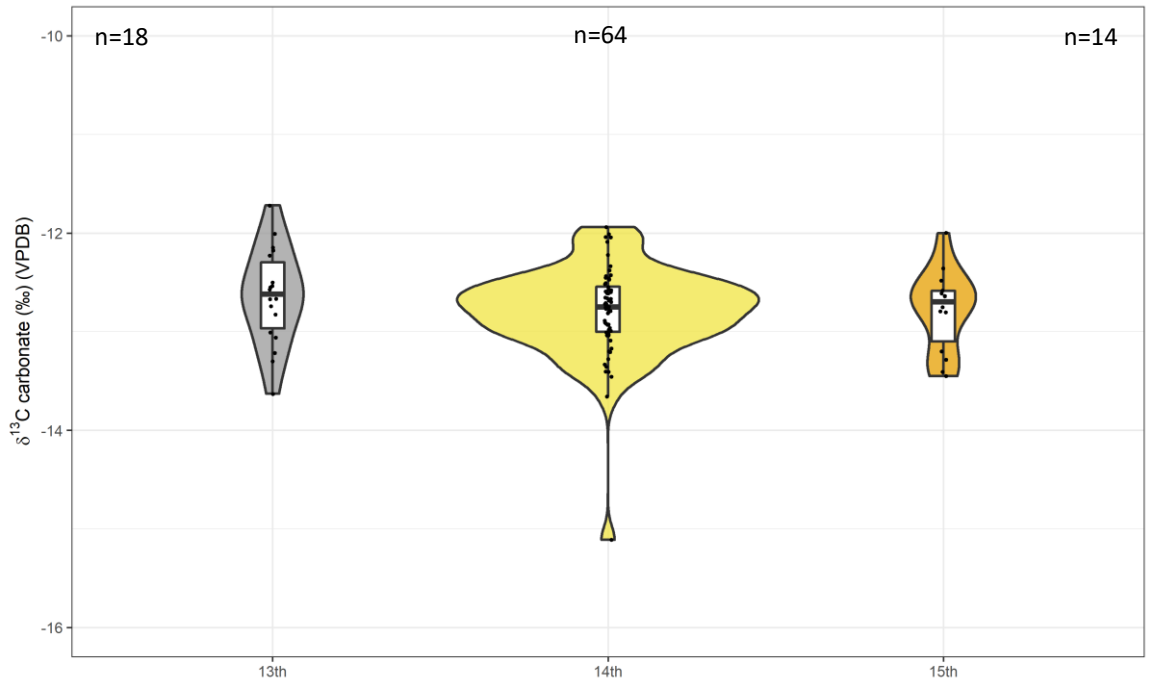


Figure 101: Violinplots showing tooth enamel carbonate $\delta^{13}C$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

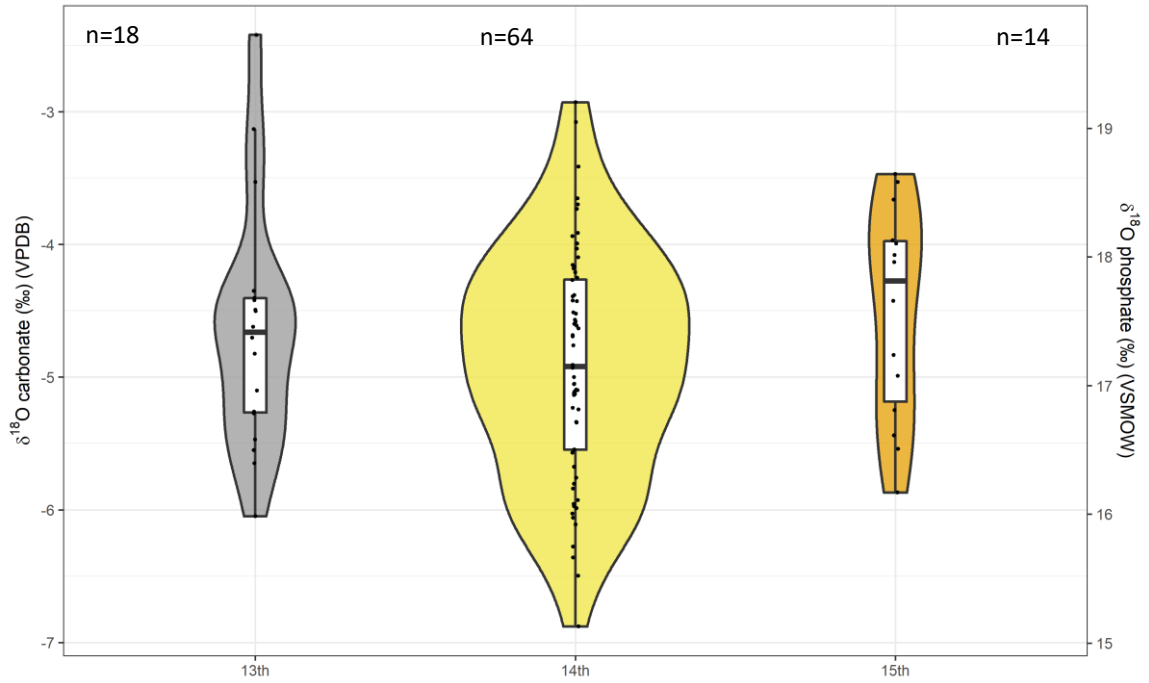


Figure 102: Violinplots showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

Enamel $^{87}Sr/^{86}Sr$

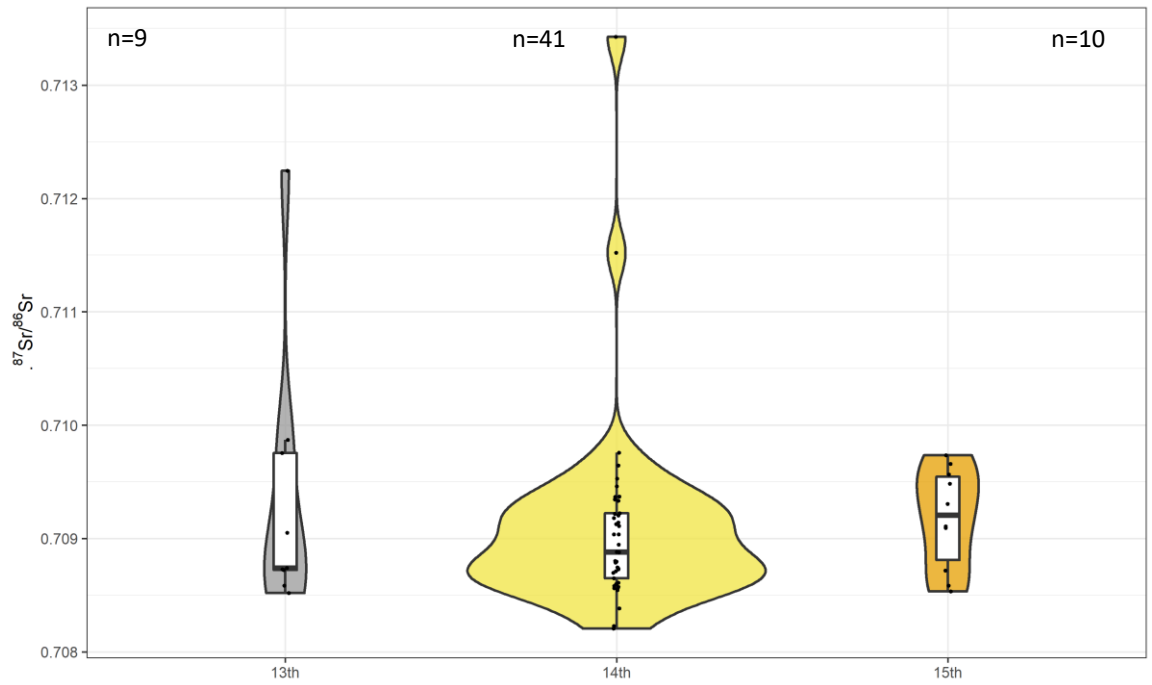


Figure 103: Violinplots showing tooth enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

Enamel Carbonate $\delta^{18}O$ and Enamel $^{87}Sr/^{86}Sr$

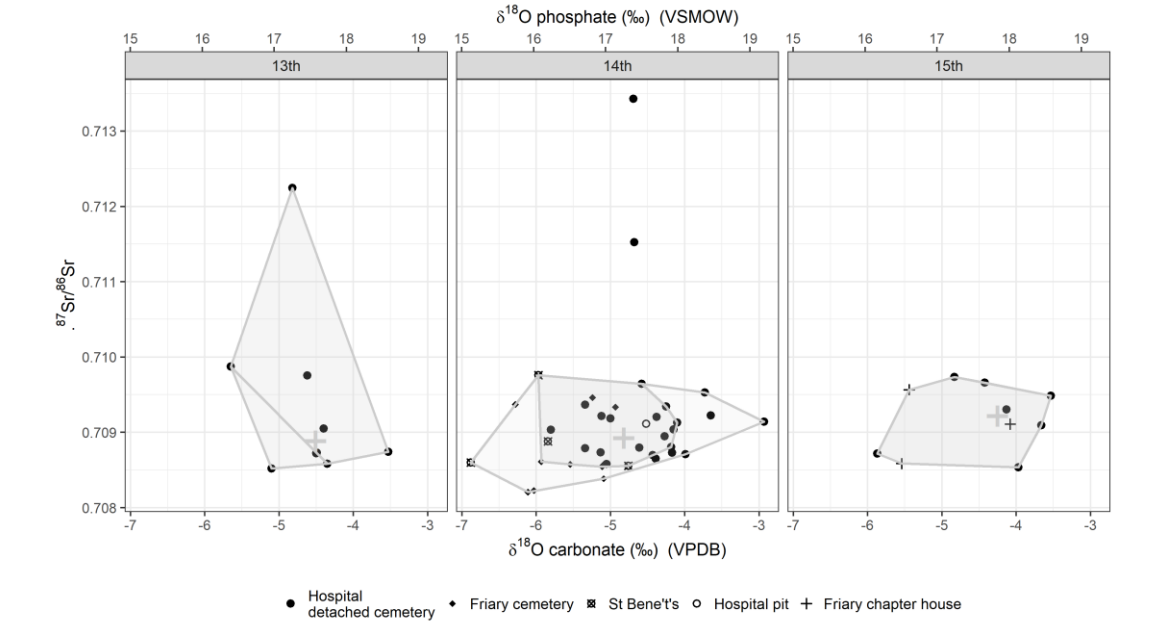


Figure 104: Bagplots showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) and enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date

7.8.2 Results: Medieval Century and Site Subgroup (and Sex)

As discussed in section 7.7.4 for the pre/post-1350 data, the approach of combining data from several site subgroups into century groups may mask more nuanced changes, so this section discusses the only subgroup with data from all three Medieval centuries – the Hospital detached cemetery.

The Hospital data shows an increase in dentine mean $\delta^{13}C$ values through time and an overall decrease in mean $\delta^{15}N$ values from the 13th to 15th centuries, although the lowest values are seen in the 14th century (11.7‰) (Table 55). The difference in the range and distribution of dentine $\delta^{13}C$ values in the 15th century is quite distinct from the previous centuries, as can be seen in Figure 105. Unlike dentine, the mean rib collagen $\delta^{13}C$ values remain very similar through time and the mean rib $\delta^{15}N$ values only show an increase in the 15th century (Table 56, Figure 106). The enamel carbonate $\delta^{13}C$ values also show little change by century (Table 57, Figure 108). The changes in dentine and rib $\delta^{13}C$ and $\delta^{15}N$ values by century are quite different between females and males (Table 55, Table 56). For example, females show no difference in mean rib $\delta^{15}N$ values between the 13th and 14th centuries but show an increase in the 15th century, whereas males show a decrease in mean $\delta^{15}N$ values in the 14th century, before increasing in the 15th century. Females also show a 0.2‰ decrease in enamel carbonate $\delta^{13}C$ from the 13th to 14th centuries, followed by a 0.5‰ increase from the 14th to 15th centuries, while males show very little change. Figure 107 further demonstrates that the difference between the range and spread of $\delta^{13}C$ and $\delta^{15}N$ values females and males is more pronounced in the 14th century. It is this increased difference between the sexes that is the most interesting trend by century and may imply some temporal changes in the social differentiation of diets, or at least temporal differences in admittance and/or burial at the Hospital (Rubin 1987).

The mean $\delta^{18}O$ values for the Hospital increase through time, with a mean of -4.7‰ in the 13th century and -4.4‰ in the 15th century (Table 58, Figure 109). The mean $\delta^{18}O$ values for males peak in the 14th century at -4.5‰ and there is a larger difference between the mean and median values for females and males in the 13th century (0.3‰) than in the 14th (0.1‰) or 15th (0.0-0.1‰). The median $^{87}Sr/^{86}Sr$ values increase slightly by century, however, at the Hospital there are only three outliers, one in the 13th and two in the 14th century (Table 59, Figure 110).

Site Subgroup	Medieval Century	Sex	n	Dentine δ13C (‰) (VPDB)						Dentine δ15N (‰) (AIR)					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	13th	**ALL**	9	-19.3	0.4	-19.6	-19.7	-18.6	1.1	13.0	1.1	12.6	11.9	15.4	3.5
		Female	5	-19.5	0.3	-19.6	-19.7	-19.1	0.6	12.6	0.7	12.3	11.9	13.6	1.7
		Male	4	-19.2	0.6	-19.2	-19.7	-18.6	1.1	13.4	1.3	12.9	12.6	15.4	2.8
	14th	**ALL**	30	-19.3	0.5	-19.3	-20.2	-18.0	2.2	11.7	1.4	11.4	9.4	15.3	5.9
		Female	13	-19.5	0.4	-19.4	-20.2	-18.8	1.4	11.7	0.8	11.9	10.3	12.8	2.5
		Male	17	-19.1	0.5	-19.1	-19.9	-18.0	1.9	11.6	1.8	11.1	9.4	15.3	5.9
	15th	**ALL**	8	-18.9	0.5	-18.8	-19.9	-18.3	1.6	12.5	1.1	12.6	10.6	14.0	3.4
		Female	2	-18.5	0.3	-18.5	-18.7	-18.3	0.4	12.9	0.8	12.9	12.3	13.4	1.1
		Male	6	-19.0	0.5	-18.9	-19.9	-18.6	1.3	12.3	1.2	12.3	10.6	14.0	3.4

Table 55: Summary statistics for dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval individuals from the Hospital detached cemetery only, by High/Late Medieval century and sex (adults only).

Site Subgroup	Medieval Century	Sex	n	Rib δ13C (‰) (VPDB)						Rib δ15N (‰) (AIR)					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	13th	**ALL**	36	-19.0	0.4	-19.0	-19.7	-17.7	2.0	12.5	1.0	12.6	10.3	14.7	4.4
		Female	16	-19.2	0.4	-19.1	-19.7	-18.2	1.5	12.2	0.9	12.2	10.3	14.0	3.7
		Male	17	-18.9	0.4	-18.9	-19.5	-17.7	1.8	12.8	1.1	13.1	10.6	14.7	4.1
	14th	**ALL**	46	-19.0	0.4	-19.1	-19.8	-18.1	1.7	12.4	1.2	12.4	9.7	15.2	5.5
		Female	17	-19.3	0.4	-19.3	-19.8	-18.7	1.7	12.2	1.0	12.2	10.8	14.4	3.6
		Male	27	-18.9	0.4	-19.0	-19.6	-18.1	1.5	12.5	1.4	12.4	9.7	15.2	5.5
	15th	**ALL**	13	-18.9	0.3	-18.8	-19.5	-18.3	1.2	12.9	0.9	12.8	11.4	14.0	3.6
		Female	3	-18.7	0.1	-18.7	-18.8	-18.6	0.2	12.8	1.1	12.8	11.7	13.8	2.1
		Male	10	-18.9	0.4	-18.9	-19.5	-18.3	1.2	12.9	1.0	13.1	11.4	14.0	3.6

Table 56: Summary statistics for rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval individuals from the Hospital detached cemetery only, by High/Late Medieval century and sex

Site Subgroup	*Medieval Century*	*Sex*	*n*	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	13th	**ALL**	18	-12.6	0.5	-12.6	-13.6	-11.7	1.9
		Female	7	-12.7	0.5	-12.7	-13.3	-11.7	1.6
		Male	8	-12.7	0.5	-12.7	-13.6	-12.0	1.6
	14th	**ALL**	42	-12.8	0.5	-12.7	-15.1	-11.9	3.2
		Female	13	-12.9	0.8	-12.6	-15.1	-12.0	3.1
		Male	20	-12.7	0.4	-12.8	-13.7	-12.0	1.7
	15th	**ALL**	11	-12.6	0.3	-12.6	-13.2	-12.0	1.2
		Female	2	-12.4	0.1	-12.4	-12.5	-12.4	0.1
		Male	6	-12.6	0.4	-12.6	-13.2	-12.0	1.2

Table 57: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for High/Late Medieval individuals from the Hospital detached cemetery only, by High/Late Medieval century and sex (adults only).

Site Subgroup	*Medieval Century*	*Sex*	*n*	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						*Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)*					
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Hospital detached cemetery	13th	**ALL**	18	-4.7	0.9	-4.7	-6.0	-2.4	3.6	17.3	1.0	17.3	15.8	19.6	3.8
		Female	7	-4.7	0.9	-4.8	-5.7	-3.1	2.6	17.2	0.9	17.1	16.2	18.9	2.7
		Male	8	-4.3	1.0	-4.5	-6.0	-2.4	3.6	17.6	1.1	17.4	15.8	19.6	3.8
	14th	**ALL**	42	-4.6	0.7	-4.5	-6.1	-2.9	3.2	17.4	0.8	17.4	15.8	19.1	3.3
		Female	13	-4.6	0.7	-4.6	-5.8	-2.9	2.9	17.3	0.8	17.3	16.0	19.1	3.1
		Male	20	-4.5	0.7	-4.5	-6.0	-3.1	2.9	17.4	0.7	17.5	15.9	18.9	3.0
	15th	**ALL**	11	-4.4	0.8	-4.1	-5.9	-3.5	2.4	17.6	0.8	17.8	16.0	18.5	2.5
		Female	2	-4.2	0.3	-4.2	-4.4	-4.0	0.4	17.8	0.3	17.8	17.5	18.0	0.5
		Male	6	-4.2	0.6	-4.1	-5.0	-3.5	1.5	17.8	0.6	17.9	16.9	18.5	1.6

Table 58: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval individuals from the Hospital detached cemetery only, by High/Late Medieval century and sex (adults only)

Site Subgroup	***Medieval Century***	***Sex***	***n***	**Enamel $^{87}Sr/^{86}Sr$**						**Sr ppm**	
				Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*
Hospital detached cemetery	13th	**ALL**	9	0.7094	0.0012	0.7087	0.7085	0.7122	0.0037	124	38
		Female	3	0.7102	0.0019	0.7099	0.7086	0.7122	0.0036	150	51
		Male	5	0.7090	0.0004	0.7087	0.7087	0.7098	0.0011	118	22
	14th	**ALL**	24	0.7093	0.0011	0.7091	0.7086	0.7134	0.0048	124	33
		Female	12	0.7090	0.0003	0.7090	0.7086	0.7094	0.0008	133	31
		Male	11	0.7097	0.0015	0.7092	0.7087	0.7134	0.0047	113	34
	15th	**ALL**	7	0.7092	0.0005	0.7093	0.7085	0.7097	0.0012	110	29
		Female	2	0.7091	0.0008	0.7091	0.7085	0.7097	0.0012	112	25
		Male	4	0.7094	0.0003	0.7094	0.7091	0.7097	0.0006	117	33

Table 59: Summary statistics for tooth enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval individuals from the Hospital detached cemetery only, by High/Late Medieval century and sex (adults only)

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

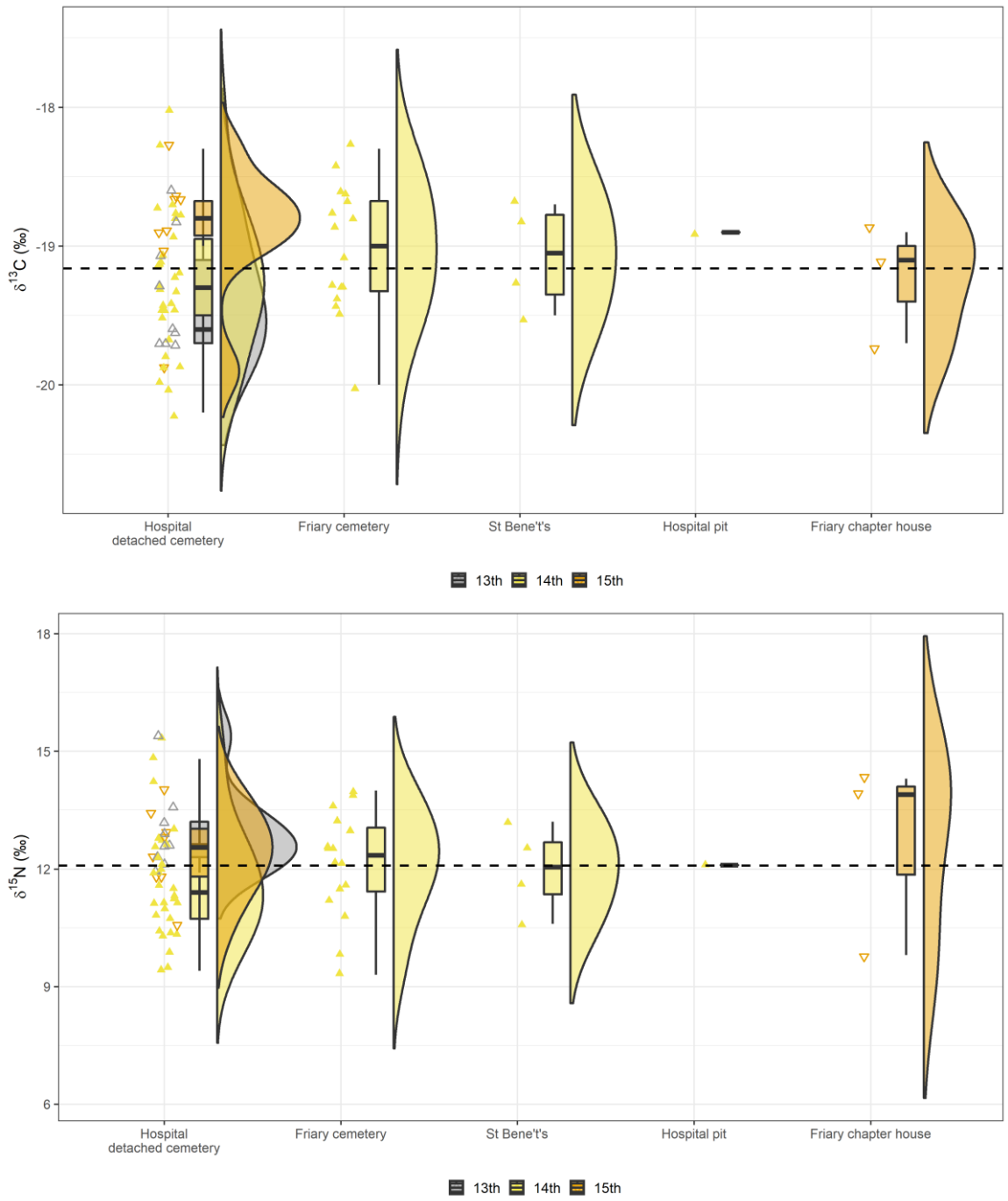


Figure 105: Raincloud plots showing dentine collagen $\delta^{13}C$ and $\delta^{15}N$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Rib Collagen $\delta^{13}C$ and $\delta^{15}N$

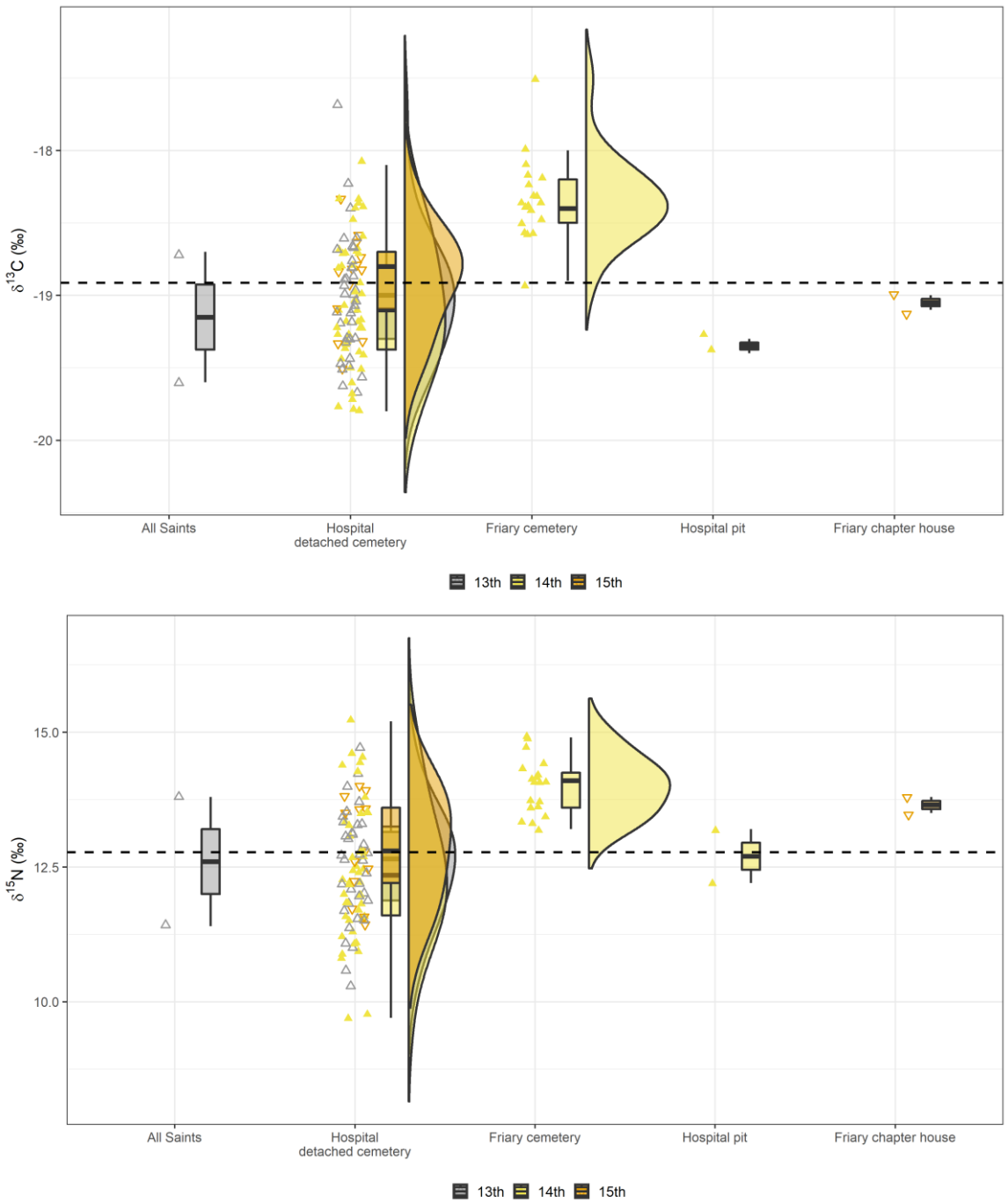


Figure 106: Raincloud plots showing rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

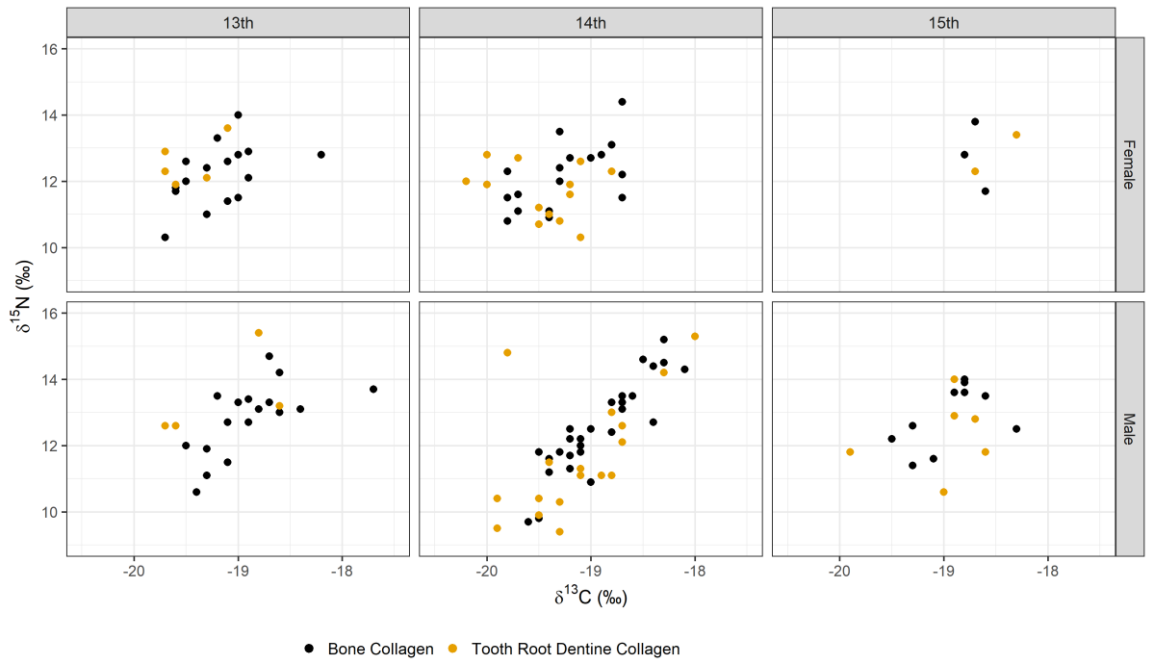


Figure 107: Scatterplots showing dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult individuals from the hospital detached cemetery only who were assigned a 13th, 14th or 15th century date and assigned a female/male sex estimate (faceted by date and sex)

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

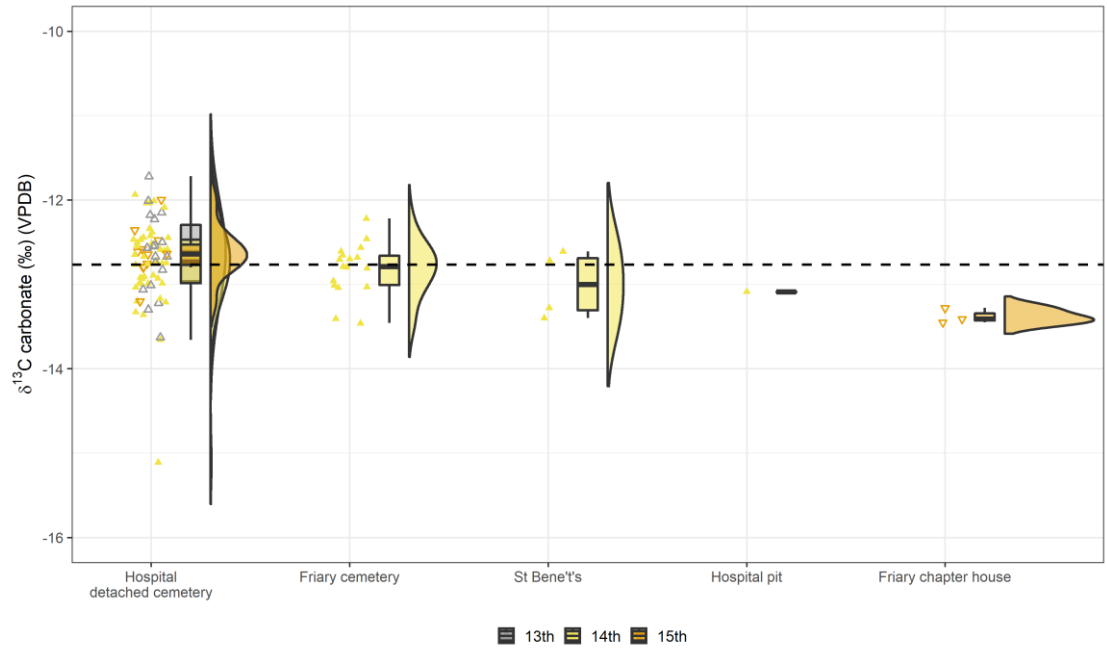


Figure 108: Raincloud plot showing tooth enamel carbonate $\delta^{13}C$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

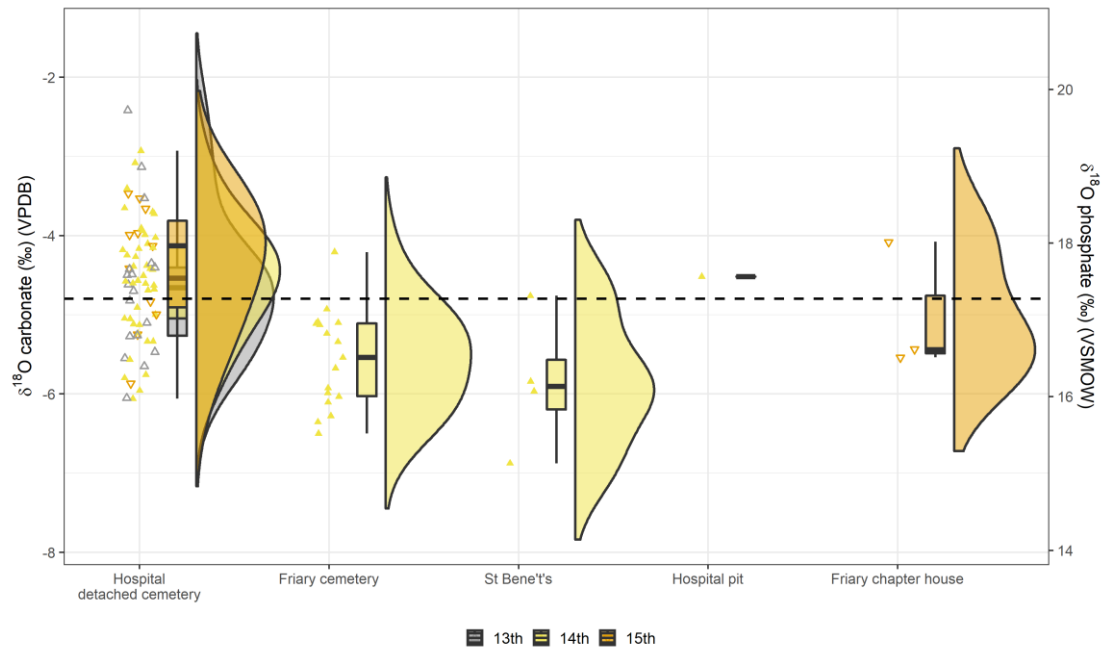


Figure 109: Raincloud plot showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

Enamel $^{87}Sr/^{86}Sr$

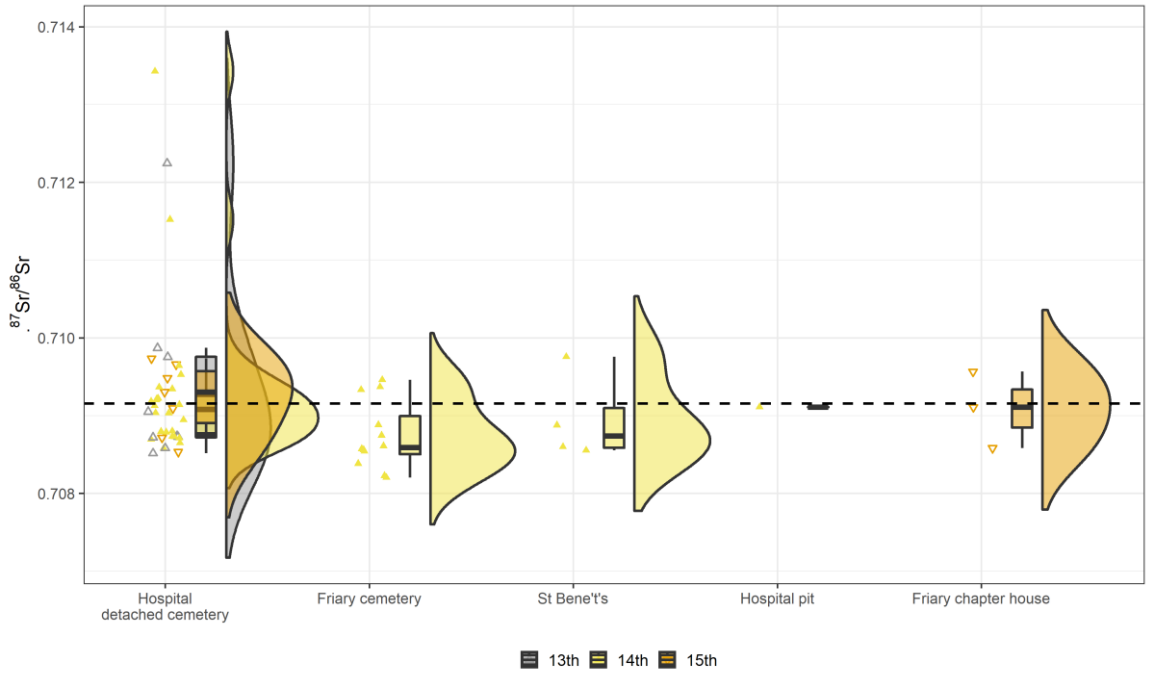


Figure 110: Raincloud plot showing tooth enamel $^{87}Sr/^{86}Sr$ values for High/Late Medieval Cambridgeshire individuals who were assigned a 13th, 14th or 15th century date, by site subgroup. Dashed line indicates the mean isotope value for all the individuals represented in each plot.

7.8.3 Statistical Testing: Medieval Century

Comparisons of the High/Late Medieval isotope data by Medieval Century indicates that only dentine collagen $\delta^{15}N$ values were unlikely to be taken from a population with equal means (one-way ANOVA $\delta^{15}N$: p=0.042). However, all pairwise comparisons using Tukey's post-hoc test produced adjusted p-values >0.05. Comparisons of the isotope data by century from the Hospital detached cemetery only also indicates that only dentine collagen $\delta^{15}N$ values were unlikely to be taken from a population with equal means (one-way ANOVA: $\delta^{15}N$: p=0.03). Tukey's post-hoc shows a difference in means between the 13th and 14th century ($p.adj$=0.0342).

When the overall High/Late Medieval data is broken down to compare females and males by century, adult dentine collagen and adult rib collagen $\delta^{13}C$ data is unlikely to be taken from populations with equal means (one-way ANOVA: dentine $\delta^{13}C$: p=0.039; rib $\delta^{13}C$: p=<0.0001). However, for dentine $\delta^{13}C$, Tukey's post-hoc test again shows no pairwise comparisons with adjusted p-values <0.05. For rib collagen $\delta^{13}C$, post-hoc tests appear to show a difference in means between 13th-century females and 14th century males (rib $\delta^{13}C$: $p.adj$=0.0021) as well as a difference between 14th century females and 14th century males (rib $\delta^{13}C$: $p.adj$=<0.0001). When the Hospital detached cemetery only is analysed by sex and century, only adult rib collagen $\delta^{13}C$ values appear to be unlikely to be taken from populations of equal means (one-way ANOVA: rib $\delta^{13}C$: p=0.021), although no pairwise comparisons produce adjusted p-values <0.05 when analysed with Tukey's post-hoc test. In cases where post-hoc tests did not show adjusted p-values <0.05, I decided that this suggests no meaningful difference in the mean isotope values.

7.8.4 Summary: Medieval Century

Analysis of the data by Medieval century is severely hampered by the uneven sample sizes and lack of sites which span multiple centuries, making characterisation of the data by century very difficult. The plots may indicate some overall changes by century but statistically, these changes are not meaningful and may just be a product of combining several site types.

The Hospital detached cemetery is the only site with data for all three centuries, providing a more robust temporal comparison. Changes in the $\delta^{13}C$ and $\delta^{15}N$ values may indicate some changes in diet through the centuries, particularly in childhood as evidenced by the changing dentine $\delta^{13}C$ values (Richards *et al.* 2002, Burt 2015). The most important change may be

differences in diet by sex, with values for females and males diverging in the 14th century and becoming less varied in the 15th century (although the sample size for the 15th century is too small to confirm). At the Hospital there appears to be very little change in enamel carbonate $\delta^{18}O$ values through time, corroborated by statistical tests that found no difference in the values by century, although the only $\delta^{18}O$ outlier was from the 13th century. The median $^{87}Sr/^{86}Sr$ value at the Hospital detached cemetery shows an increase by century and there was some divergence in the probability density of the data by century, although most of the data is within the 'local' range. There are outliers present in the 13th and 14th century only, although there are only three. Overall, there does not appear to be a meaningful difference in the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values by century. There is no evidence of substantially increased numbers of 'non-locals' in any one century, although there are no outliers in the 15th century.

7.9 High/Late Medieval Human Isotope Results by Inter- and Intra-Individual Differences

The previous sections have looked at the High/Late Medieval isotope data by site subgroup, as well as by social and temporal factors, with varying success. This section takes a different approach and investigates inter- and intra-individual changes. In particular, this section looks at dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values together to try and assess the experiences within the lifecourse of individual people in the High/Late Medieval period.

7.9.1 Inter- and Intra-Individual Changes in $\delta^{13}C$ and $\delta^{15}N$ values

Figure 111 presents adult dentine and rib $\delta^{13}C$ and $\delta^{15}N$ values overlain to show the differences in the data by tissue, and very clearly shows inter- and intra-site differences. There is a larger difference between dentine and rib isotope values at the Friary, with the dentine isotope values having an elongated spread and the rib isotope values being tightly clustered with comparatively high $\delta^{15}N$ values. This indicates a much bigger difference between the childhood and adulthood diet of individuals who entered the Friary than other sites. The narrow rib $\delta^{13}C$ and $\delta^{15}N$ range could indicate adoption of an institutionalised diet (dietary shifts also seen in two Medieval friaries in northern England (Kancle *et al.* 2018)). At All Saints, the inner bags for dentine and rib $\delta^{13}C$ and $\delta^{15}N$ values are the most similar, potentially indicating the least change between childhood and adulthood, although there is variation in the outer values. At the Hospital, the range is much wider than other sites. The dentine and rib values at the Hospital overlap, but the rib values are more constricted, perhaps hinting at a wide catchment area or cross-section of society that enter the Hospital and an institutionalised diet once they do enter.

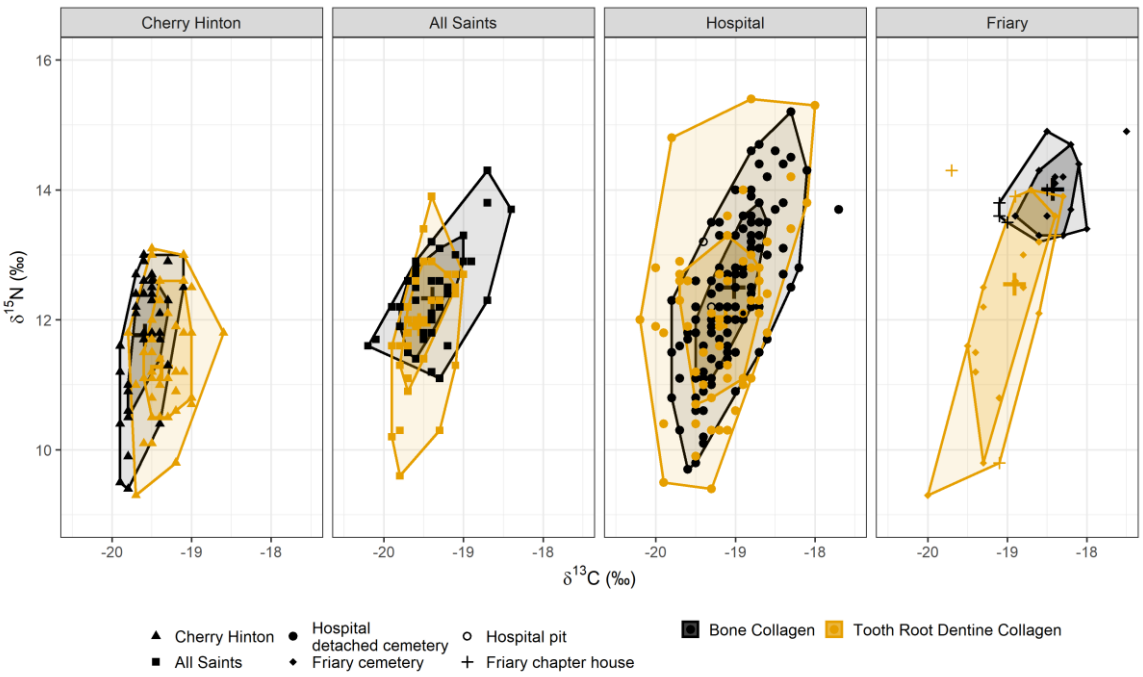


Figure 111: Bagplots with scatterplots showing dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals (faceted by overall site)

The difference between dentine and rib collagen isotope values was calculated for each individual where both dentine and rib was sampled to investigate changes between tissues in individuals. This involved subtracting dentine isotope values from rib isotope values to create $\Delta_{Rib\text{-}Dent}$ values. The mean $\Delta^{13}C_{Rib\text{-}Dent}$ is negative at some sites and positive at others, with the Friary cemetery displaying the largest overall change (+0.7‰) (Table 60, Figure 112). The mean $\Delta^{15}N_{Rib\text{-}Dent}$ values are positive for all site subgroups, with the Friary cemetery displaying the largest overall change (+1.6‰). The Hospital detached cemetery has the biggest $\Delta^{13}C_{Rib\text{-}Dent}$ & $\Delta^{15}N_{Rib\text{-}Dent}$ range. Most of the individuals at the Friary display positive $\Delta^{13}C_{Rib\text{-}Dent}$ and $\Delta^{15}N_{Rib\text{-}Dent}$ values (most points in the top right quadrant), Cherry Hinton has negative $\Delta^{13}C_{Rib\text{-}Dent}$ values but positive $\Delta^{15}N_{Rib\text{-}Dent}$ values (most points in the top left quadrant) and the Hospital has a wide range of $\Delta^{13}C_{Rib\text{-}Dent}$ & $\Delta^{15}N_{Rib\text{-}Dent}$ values.

Figure 113 and Figure 114 illustrate dentine to rib collagen $\delta^{13}C$ and $\delta^{15}N$ value trajectories for each High/Late Medieval individual with results for both. These show how an individual's dentine and rib isotope values compare to other individuals and how they compare to the mean isotope values for each site. They also show how large the change in isotope values from dentine to rib was and whether it was a positive or negative change, indicating whether

individuals underwent significant dietary change between their childhood and adulthood. The figures are effective at showing the general spread of the data at each site, highlighting the large range at the Hospital, and the large positive changes at the Friary and they are effective at showing individuals who have unusual dentine-rib trajectories.

Most individuals analysed seem to show some degree of change in their $\delta^{15}N$ values (>0.2‰), but several individuals have relatively larger inter-tissue differences in $\delta^{13}C$ and $\delta^{15}N$ values (>1.0‰). For example, PSN 912, has the highest dentine $\delta^{13}C$ value at Cherry Hinton (-18.6‰) but her rib collagen $\delta^{13}C$ value is -19.8‰, below the average for the site. Conversely, some individuals show large positive increases in $\delta^{13}C$ values between dentine and rib, for example, PSN 509, a Friar, shows an increase of 0.9‰ between his dentine and rib collagen values. There are large positive dentine to rib changes in $\delta^{15}N$ values present at the Friary, but also at the Hospital, indicating an increase in animal proteins or marine fish consumption in adulthood (Minagawa and Wada 1984, Schoeninger and DeNiro 1984). A few decreases stand out: PSN 912 from Cherry Hinton has an above-average dentine $\delta^{15}N$ value (11.8‰) but this decreases to 9.4‰ in her rib collagen, one of the lowest values of any of the High/Late Medieval individuals who were sampled for both dentine and rib collagen. This potentially indicates a change in fortunes leading to a less animal protein rich diet. In contrast, a young male from the Hospital (PSN 31), presents consistently low $\delta^{15}N$ values (dentine 9.9‰, rib: 9.8‰) and PSN 203, an old male, presents consistently high $\delta^{15}N$ values (dentine: 15.3‰, rib: 15.2‰). These individuals with little change between dentine and rib collagen values seem comparatively unusual, especially as they occur at the extremes of the isotope values recorded from the Hospital. There are several possible explanations- for example, PSN 203 could be a corrodian, eating a different, more protein-rich diet to the rest of the Hospital population (Rubin 1987) (see Sections 2.3.2 and 4.5.2.2). PSN 31 is more difficult to explain but they seem to have consistently consumed less animal protein than others in the Hospital. These changes allow for discussion of diet on an individual scale and will be explored further in the discussion.

Site Subgroup	*Sex*	*n*	$\Delta^{13}C_{Rib\text{-}Dent}$ (‰) (VPDB)						$\Delta^{15}N_{Rib\text{-}Dent}$ (‰) (AIR)					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Cherry Hinton	**ALL**	39	-0.3	0.3	-0.2	-1.2	0.1	1.3	0.3	0.8	0.4	-2.4	2.1	4.5
	Female	17	-0.2	0.3	-0.2	-1.2	0.1	1.3	0.2	0.9	0.5	-2.4	1.4	3.8
	Male	22	-0.3	0.2	-0.3	-0.7	0.1	0.8	0.3	0.7	0.4	-1.2	2.1	3.3
All Saints	**ALL**	13	0.1	0.4	0.3	-0.7	0.7	1.4	0.4	0.9	0.2	-1.3	1.9	3.2
	Female	4	0.0	0.5	0.0	-0.4	0.4	0.8	0.4	1.0	0.1	-0.5	1.8	2.3
	Male	9	0.2	0.4	0.3	-0.7	0.7	1.4	0.4	0.9	0.2	-1.3	1.9	3.2
Hospital detached cemetery	**ALL**	53	0.1	0.4	0.1	-0.6	1.0	1.6	0.5	1.2	0.5	-2.7	3.5	6.2
	Female	23	0.1	0.4	0.1	-0.6	0.8	1.4	0.3	1.0	0.3	-1.5	3.2	4.7
	Male	30	0.1	0.4	0.1	-0.6	1.0	1.6	0.7	1.3	0.8	-2.7	3.5	6.2
Friary cemetery	**ALL**	12	0.7	0.4	0.8	-0.2	1.2	1.4	1.6	1.0	1.9	-0.4	3.4	3.8
	Male	12	0.7	0.4	0.8	-0.2	1.2	1.4	1.6	1.0	1.9	-0.4	3.4	3.8
Hospital pit	**ALL**	1	-0.5	-	-0.5	-0.5	-0.5	-	1.1	-	1.1	1.1	1.1	-
	Female	1	-0.5	-	-0.5	-0.5	-0.5	-	1.1	-	1.1	1.1	1.1	-
Friary chapter house	**ALL**	2	-0.2	0.1	-0.2	-0.2	-0.1	0.1	0.3	0.6	0.3	-0.1	0.7	0.8
	Male	2	-0.2	0.1	-0.2	-0.2	-0.1	0.1	0.3	0.6	0.3	-0.1	0.7	0.8

Table 60: Summary statistics for rib-dentine collagen $\Delta^{13}C$ and $\Delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were sampled for both dentine and rib

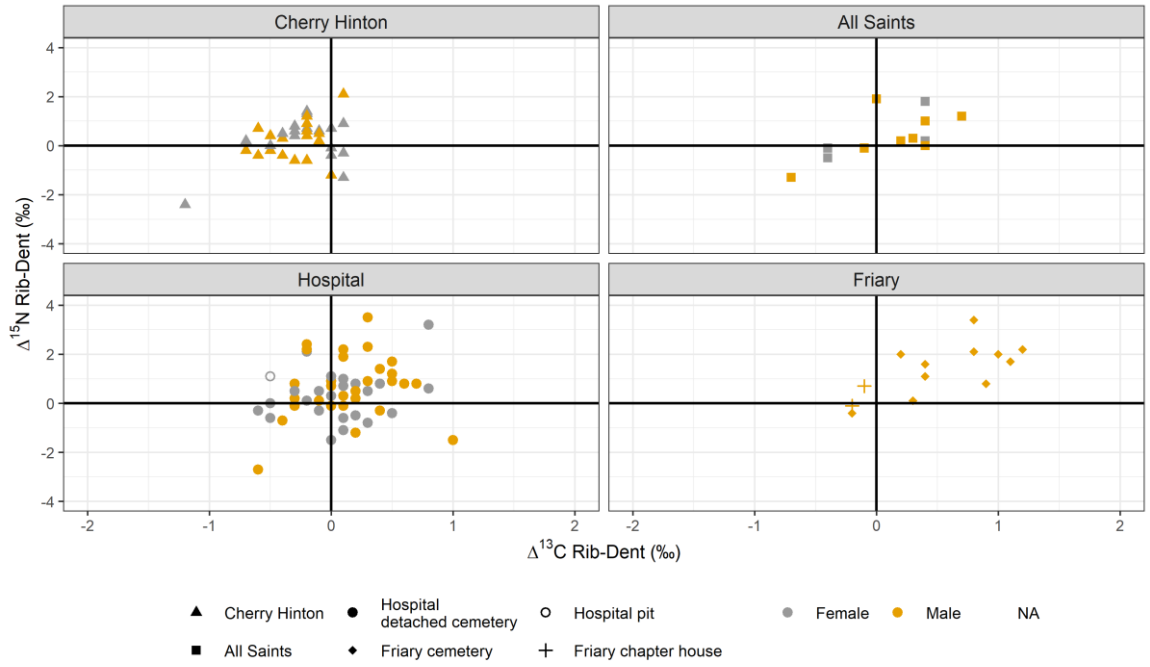


Figure 112: Scatterplots showing rib-dentine collagen $\Delta^{13}C$ and $\Delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were sampled for both dentine and rib (faceted by overall site)

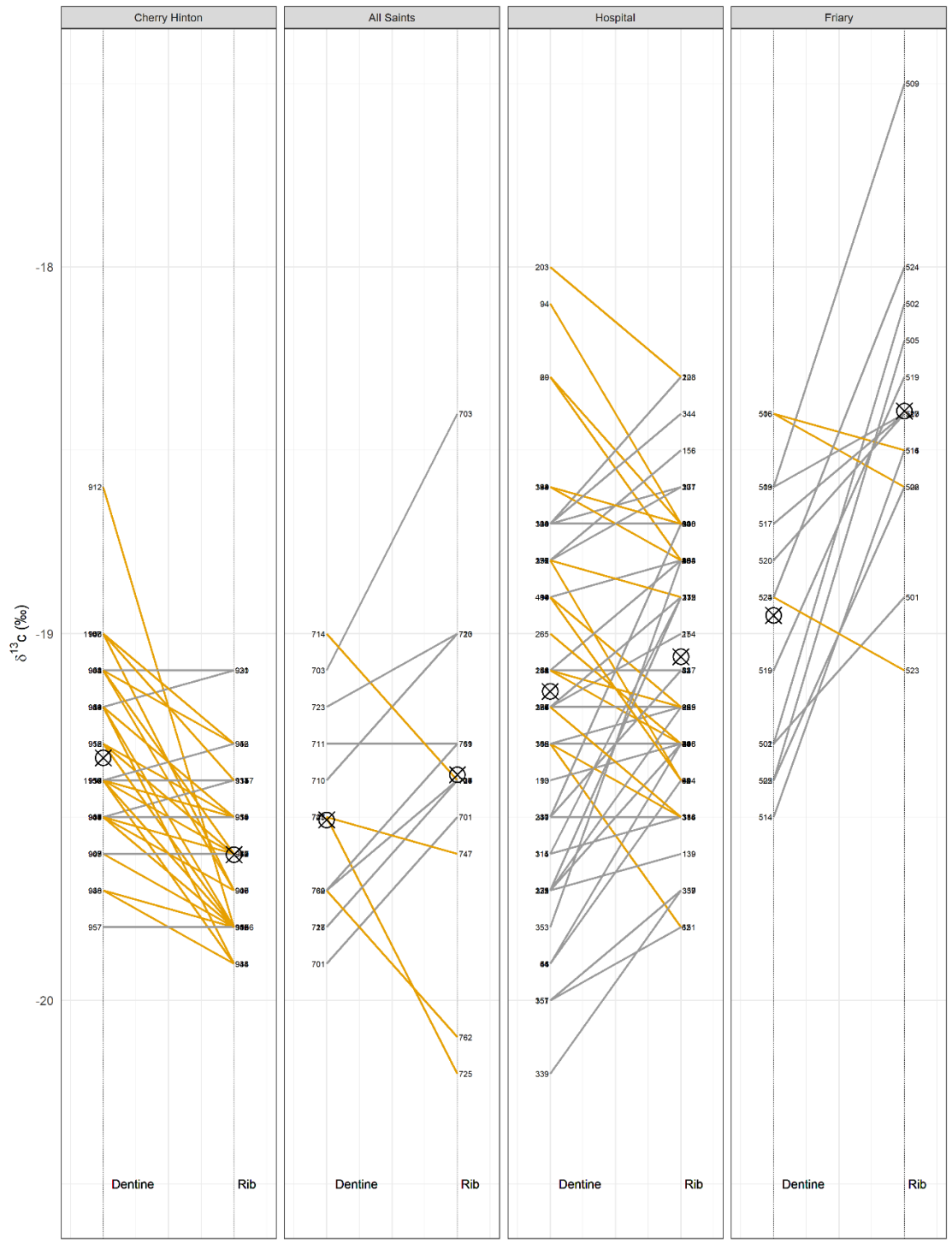


Figure 113: Slopeplots showing individual change between dentine and rib collagen $\delta^{13}C$ values for adult High/Late Medieval Cambridgeshire individuals who were sampled for both dentine and rib (faceted by overall site).
Grey lines indicate dentine $\delta^{13}C$ values < rib $\delta^{13}C$ values, orange lines indicate dentine $\delta^{13}C$ values > rib $\delta^{13}C$ values. Circle/cross symbols indicate the mean dentine or rib C isotope value for all the individuals represented in each plot. Individuals are labelled by PSN number.

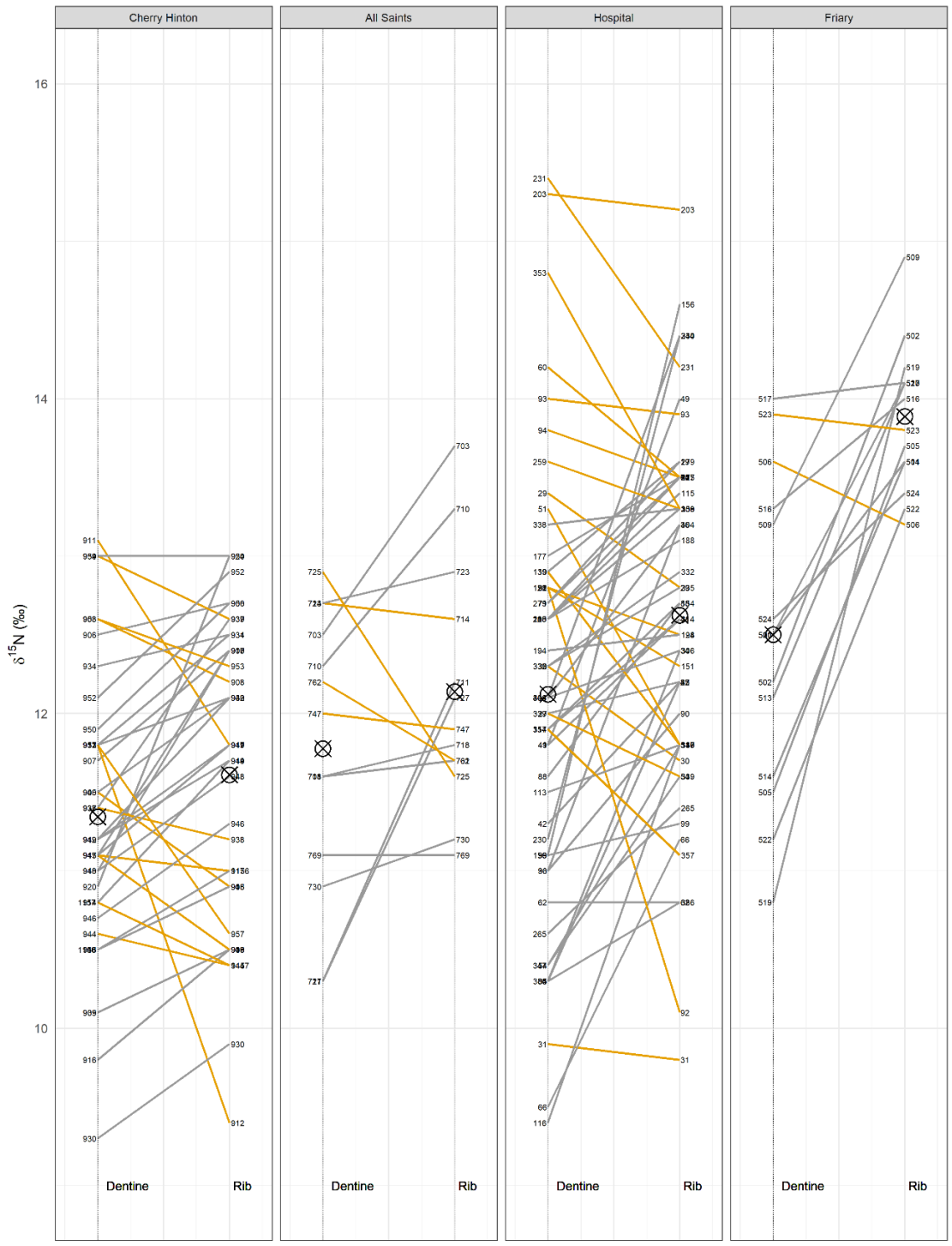


Figure 114: Slopeplots showing individual change between dentine and rib collagen $\delta^{15}N$ values for adult High/Late Medieval Cambridgeshire individuals who were sampled for both dentine and rib (faceted by overall site).
Grey lines indicate dentine $\delta^{15}N$ values < rib $\delta^{15}N$ values, orange lines indicate dentine $\delta^{15}N$ values > rib $\delta^{15}N$ values.
Circle/cross symbols indicate the mean dentine or rib N isotope value for all the individuals represented in each plot. Individuals are labelled by PSN number.

7.9.2 Detecting Deviating Data Cells

The previous sections have largely considered results from each isotope and tissue individually or in pairs. In order to consider all of the available isotope data together, 'Detect Deviant Cell' (DDC) analysis (Rousseeuw and Bossche 2018) was applied to the High/Late Medieval adults, to identify any individuals who are outliers in the context of all available isotope data (see Section 5.4.2 for method).

All suitable isotope data for High/Late Medieval adults was inputted, resulting in 262 rows (individual skeletons) and 11 columns (isotope data). 106 rows were rejected by the initial DDC data check as they contained over 50% of cells with NAs, i.e. individuals that did not have many isotope results. Therefore, the final dataset for DDC contained 156 High/Late Medieval adults.

The DDC output (Figure 115) highlighted 23 individuals (15%) who were flagged as deviating either higher than the predicted values (red) or lower than the predicted values (blue) for the major isotope analyses in this thesis (Table 61). Several of the individuals highlighted have been noted as outliers in previous sections, but DDC has flagged more than detected previously. There does not appear to be any pattern between the deviating individuals and their characteristics- they are from across the site subgroups, across time periods and comprise of both sexes and a range of ages, indicating that no one 'type' of person is detectably different to the rest of the High/Late Medieval population in Cambridge. Only two individuals were flagged for deviating in dentine collagen $\delta^{13}C$ *and* $\delta^{15}N$ values: PSN 203 and 912. No individuals were flagged for deviating in both $\delta^{13}C$ *and* $\delta^{15}N$ values for rib collagen and no individuals were flagged for deviating in both $\delta^{18}O$ *and* $^{87}Sr/^{86}Sr$ values, making interpretation of the deviances more complex. For $\delta^{13}C$ and $\delta^{15}N$, PSNs 203 and 912 stand out as individuals with multiple deviating cells. Both individuals were previously identified in Section 7.9.1 as having usual dietary trajectories. Seven individuals deviate in $^{87}Sr/^{86}Sr$ values but only one individual deviates in carbonate $\delta^{18}O$ values. All these individuals have been identified as outliers in previous sections, but this analysis confirms they are robustly different from the rest of the population and are the most likely to not have spent their childhoods in Cambridge. These will be discussed further in Chapter 9.



Figure 115: cellWise output from DetectDeviantCells (DDC) analysis for 156 medieval adults. Cell colour key: yellow = default, red = higher than predicted, blue = lower than predicted, orange/purple = intermediate, white = no data. Values are 'true' values (not imputed)

PSN	Site Subgroup	Est Date	Sex	Broad Age	Dent		Rib		Enamel		
					$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{18}O$	$^{87}Sr/^{86}Sr$
66	Hospital detached cemetery	Late Med 1270-1380	M	Y							+
92	Hospital detached cemetery	Late Med 1375-1427	M	O		+		-			
94	Hospital detached cemetery	Late Med 1370-1413	F	Y	+						
99	Hospital detached cemetery	Late Med 1330-1400	M	M							+
156	Hospital detached cemetery	Late Med 1332-1415	M	M		-					
203	Hospital detached cemetery	Late Med 1250-1450	M	O	+	+					
231	Hospital detached cemetery	Late Med 1240-1350	M	O		+					
331	Hospital detached cemetery	High Med 1204-1310	F	O			+				
332	Hospital detached cemetery	Late Med 1264-1308	F	Y							+
339	Hospital detached cemetery	Late Med 1370-1511	F	M					-		
356	Hospital detached cemetery	High Med 1221-1289	M	O			-				
509	Friary cemetery	Late Med 1290-1349	M	M			+				
519	Friary cemetery	Late Med 1320-1349	M	M		-					
728	All Saints	High Med 1050-1365	F	M						-	
746	All Saints	High Med 1050-1250	M	M					-		+
912	Cherry Hinton	High Med 1000-1170	F	O	+	+		-	-		
918	Cherry Hinton	High Med 940-1100	M	M							+
930	Cherry Hinton	High Med 940-1170	F	M							+
949	Cherry Hinton	High Med 940-1170	M	O					-		
1234	Clopton	Late Med 1200-1561	F	M					-		
1238	Clopton	Late Med 1200-1561	M	M							+
1251	Clopton	Late Med 1200-1400	M	M					-		
1274	Clopton	Late Med 1348-1561	M	M					-		

Table 61: Summary of medieval adult individuals flagged for having cell values higher (+) or lower (-) than predicted, using DetectDeviantCells (DDC) analysis. Broad Age key: Y=Young Adult (18-25yr), M=Middle Adult (26-45yr), O=Old Adult (45+yr). Individuals highlighted as outliers in Section 7.4.2 highlighted in grey.

7.9.3 Summary of High/Late Medieval Inter- and Intra- Individual Isotope Differences

This section has taken an individualised approach and has demonstrated the utility of multi-isotope data to identify inter-and intra-individual differences in the High/Late Medieval population of Cambridge. Meaningful differences between dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values have been demonstrated, providing considerable information about inter- and intra-individual changes in diet through the lifecourse. This section has demonstrated the variation within single individuals, but also further characterises the differences in experience of those buried at different sites. In particular, the pattern seen in the Friary, with a large range in the dentine values, but a very narrow range in the rib collagen isotope values and the overwhelmingly positive $\Delta^{13}C_{\text{Rib-Dent}}$ and $\Delta^{15}N_{\text{Rib-Dent}}$ values could be evidence of institutionalised diet within the Friary, with diet becoming homogenous across the group once they are initiated into the religious lifestyle (Kancle *et al.* 2018). The DDC analysis of all the combined isotope data has identified several individuals who deviate from predicted values, either indicating that their diet was considerably different to the general population or that they were unlikely to have spent their childhoods in Cambridge. Following discussions in Chapter 3, however, it should also be considered that deviations in $\delta^{13}C$ and $\delta^{15}N$ values may also be indicative of individuals under metabolic stress (Schoeller 1999, Fuller *et al.* 2005). It should be noted that pooling all of the Medieval adults for DDC analysis may 'mask' some deviation that may be present on a site-by-site basis, but by this same logic, anyone who deviates in the context of the pooled data may be considered robust general outliers to the whole High/Late Medieval population.

7.10 Summary of High/Late Medieval Isotope Results

This chapter has explored the results of isotope analysis of multiple tissues from many High/Late Medieval individuals from multiple sites in Cambridgeshire, in order to address the research questions relating to diet and mobility.

Firstly, a faunal 'isotopic baseline' has been established for High/Late Medieval Cambridge, characterising the isotope values for a variety of taxa, as well as establishing that there was little overall change in the herbivore values post-1350. Some fauna did show post-1350 changes in $\delta^{15}N$ values, which may indicate changes in husbandry practices through time.

The human and faunal isotope results have allowed for a general characterisation of diet and mobility in High/Late Medieval Cambridge. Section 7.2 characterised the general dietary signature, demonstrating a largely terrestrial C_3 based diet, with variable contributions of terrestrial animal and marine proteins. Analysis of carbon isotopes in various tissues has further demonstrated the predominantly C_3 based nature of the diet and the contribution of marine proteins at some sites. Section 7.3 characterised the general level of detectable mobility in High/Late Medieval Cambridge, indicating that most individuals fell within the estimated 'local' $^{87}Sr/^{86}Sr$ range. The strontium isotope data is quite novel in that the sampling strategy was not focussed on 'special' cases but took a broader approach. This is reflected in the general homogeneity of the data, allowing for a fairly robust characterisation of the 'local' $^{87}Sr/^{86}Sr$ signature for Cambridge and the surrounding area. Section 7.3 also demonstrated the extremely wide and unusual variation in $\delta^{18}O$ values, which, in context with the wide variation seen through time in Section 8.1, seems unlikely to represent large numbers of 'non-locals' but may be indicative of underlying natural variation and potentially cultural modification.

Section 7.4 has demonstrated meaningful differences in carbon and nitrogen isotope values by site subgroup, indicating the place of burial, and therefore which social group that represented, was a strongly influential factor on dietary isotope results. Site subgroups are quite distinctive in their $\delta^{13}C$ and $\delta^{15}N$ values, with the Friary having high $\delta^{15}N$ values and the Hospital having a wide range, providing evidence for social stratification and institutionalised diets. No meaningful difference in oxygen and strontium isotope values were demonstrated by site

subgroup, although the $\delta^{18}O$ range was greater at some sites and beyond what might be expected in a normal population.

A meaningful difference in carbon and nitrogen isotope values between females and males has been demonstrated in multiple sections, although the patterns are nuanced, and are often outweighed by site as an influencing factor. Section 7.5 showed there is no conclusive difference in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values based on sex alone but the male $^{87}Sr/^{86}Sr$ values at All Saints and Cherry Hinton are much more tightly clustered than the female, which could hint at differential origins. Section 7.6 indicates that Parish females differed in $\delta^{18}O$ values compared to many other social groups. This could indicate some localised sex-based diversity in where individuals buried in the Parish cemetery of All Saints spent their childhoods.

Analysis of social groups in Section 7.6 effectively combined site type, sex and age to see if further patterns were demonstratable. This highlighted meaningful differences based on religious affiliation, with the Friars in particular, standing out as having distinctively different carbon and nitrogen isotope values to other social groups.

Section 7.9 is a particularly successful part of the analysis, demonstrating intra- and inter-individual change through the lifecourse. This section demonstrated individual isotopic trajectories and particularly highlighted the large positive increases in $\delta^{13}C$ and $\delta^{15}N$ from dentine to rib at the Friary. This section is somewhat of a novel approach and provides some of the most revealing data about individual diet. The DDC analysis in Section 7.9.2 also identified robust outliers in the data. The most interesting and conclusive results of the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ are the outliers. There are very few $\delta^{18}O$ outliers and these varied depending on how the data was grouped. The most convincing outlier for $\delta^{18}O$ is PSN 728, whose low value is unusual for Britain. There are seven to nine convincing $^{87}Sr/^{86}Sr$ outliers, depending on how the data is grouped. The values of these outliers make it likely that these individuals spent their childhood outside of Cambridge. The data show that there does not appear to be any meaningful difference in the numbers of individuals who are outliers between sites and social groups, demonstrating that no one 'type' of person was likely to be mobile, although none of the main outliers are from the Friary, which may contradict assumptions about the high mobility of Friars as discussed in Chapter 2.

Demonstrating differences by pre- or post-1350 or by Medieval century has proven to be a difficult task and problems with appropriate sample size, groupings and representation of site types across the time periods mean that time-based analyses are flawed. Overall, there is no conclusive evidence of change in isotope values post-1350, when considered by pre/post-1350 only. If there are changes, they are more subtle and there are hints that there may have been more diversity in diet pre-1350, and this diversity reduced post-1350. Analysis of the $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values by time period were inconclusive but ultimately did not show overall increased diversity or increased numbers of outliers in any one period. However, there are some patterns and clustering within the 'local' $^{87}Sr/^{86}Sr$ values at the Hospital detached cemetery that may indicate increased diversity post-1350.

In summary, this chapter has used the isotope data to successfully address questions about diet and mobility in High/Late Medieval Cambridge, demonstrating differences based on site, sex and social groupings. Key findings from this chapter will be discussed further in Chapter 9.



8. Longue Durée Isotope Results and Preliminary Discussion

To place the changes observed in the High/Late Medieval isotope data into context, this section broadens out and compares human and terrestrial faunal isotope data from Cambridgeshire spanning the longue durée, from the Neolithic to the Post-Medieval. (see Section 5.1.1.5 for British archaeological/cultural periods). This section incorporates all the isotope data investigated for the High/Late Medieval period, except for $^{87}Sr/^{86}Sr$ data, as strontium isotope analysis was primarily limited to the High/Late Medieval period only. Six human individuals were analysed for $^{87}Sr/^{86}Sr$ from the Late Anglo-Saxon site of Gamlingay. However, these yielded extremely variable values, with a maximum value of 0.7158, well outside of the 'local' range for Cambridgeshire (see Appendix I). While this is a tempting avenue of research, the sample size is small, and the group does not serve the purpose of providing a representative sample for the Late Anglo-Saxon period and so have not been discussed here. The isotope data for fish is also not discussed here due to the small sample size and the fact they were predominantly from the Late Medieval period only and therefore cannot be used to create a chronologically defined longue durée baseline. Full longue durée faunal and human isotope results can be found in the full dataset, available on Apollo (https://doi.org/10.17863/CAM.71053), and summary statistics can be found in Appendix I. Further accompanying analysis of the longue durée data can be found in Appendix III. Where statistical tests are used, corresponding full statistical analysis can be found in Appendix VI.

Chapter 3 argued for the importance of incorporating faunal isotopic baselines for carbon and nitrogen isotope analysis (e.g. Bownes *et al.* 2018). For this thesis, it was considered that human-

faunal offsets were not necessary when considering High/Late Medieval data alone, as the spatial and temporal differences between the sites and their catchment areas are restricted (see section 7.1). However, the faunal isotope data does show change over the longue durée and therefore it was considered necessary to use human-faunal offset calculations when considering the human data over such a large temporal range (following previous approaches e.g. by Lightfoot *et al.* 2012, 2015, Müldner 2013). This chapter will discuss the faunal data, then discuss calculating the human-faunal offset, before presenting the resulting offset human dentine and rib collagen $\Delta^{13}C$ and $\Delta^{15}N$ values as well as the enamel carbonate isotope data. It should be noted that generating human-faunal offset values involves a crude calculation and the values are not absolute. The 'raw' (without offset) dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values can be found in Appendix III for comparison.

8.1 Longue Durée Faunal Isotope Results

There are large changes in the bone collagen $\delta^{13}C$ and $\delta^{15}N$ data through time for all terrestrial fauna, although none display a clear linear trend (Table 62, Figure 116, Appendix III). For chickens and pigs, there appears to be an increase in the range of $\delta^{13}C$ values and an overall decrease in the mean $\delta^{13}C$ and $\delta^{15}N$ values in the Early Saxon period. There is also a marked decrease in $\delta^{15}N$ values in the Late Saxon period, before a large increase in the High Medieval period. For pigs, there is a change of 1.0‰ between the mean $\delta^{15}N$ values for the High and Late Medieval periods, despite showing differences of 1.7‰ when divided by pre- or post-1350, highlighting the difficulties and potential misrepresentation that can be introduced when analysing data in different ways.

There is generally much less variation and much smaller $\delta^{13}C$ and $\delta^{15}N$ ranges for the cows and sheep/goats than the chickens and pigs through time. The herbivores appear to show an increase in $\delta^{15}N$ values from the Roman to the Middle Saxon period, then a decrease in the Late Saxon period, before an increase in the High and Late Medieval periods (Figure 116). There is a 0.7‰ mean increase in mean $\delta^{15}N$ values between the High and Late Medieval periods when the herbivores are combined. Statistical comparisons of the herbivore $\delta^{13}C$ and $\delta^{15}N$ values by time period (Appendix VI) indicate that the mean $\delta^{13}C$ values for herbivores do not change significantly through time (one-way ANOVA: p=0.798), but the $\delta^{15}N$ values do change

(Kruskal-Wallis test: p=0.0014), although the post-hoc test only indicates a difference between the Roman and Late Medieval groups (p=0.008).

Although the sites where the faunal bones were recovered from are relatively geographically close (Figure 19, Figure 20 in Chapter 4), the different type/use/status of the sites, variations in geology and diversity of food catchment areas should be taken into account when making more fine-grained interpretations of the faunal data by time period. i.e., time periods represented by faunal bone from one site only might not be representative of the isotope values expected for the more general Cambridgeshire region during that time.

Taxon	***Period***	***n***	**Bone Collagen δ^{13}C (‰) (VPDB)**						**Bone Collagen δ^{15}N (‰) (AIR)**					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Chicken/Domestic Fowl	Roman	3	-20.2	0.4	-20.2	-20.5	-19.8	0.7	10.9	1.8	10.2	9.6	12.9	3.3
	Early Saxon	5	-21.2	1.2	-20.7	-22.8	-20.2	2.6	8.4	2.1	8.3	6.4	10.8	4.4
	Middle Saxon	2	-20.1	0.1	-20.1	-20.2	-20.0	0.2	10.2	0.9	10.2	9.6	10.9	1.3
	Late Saxon	5	-20.2	0.6	-20.1	-21.1	-19.4	1.7	9.3	1.1	9.7	7.4	10.1	2.7
	High Medieval	1	-20.7	-	-20.7	-20.7	-20.7	-	11.2	-	11.2	11.2	11.2	-
	Late Medieval	19	-20.1	0.3	-20.1	-20.6	-19.7	0.9	10.6	1.5	10.6	8.0	14.1	6.1
	Post-Medieval	8	-20.5	0.5	-20.4	-21.2	-19.7	1.5	11.2	1.4	11.5	8.7	12.9	4.2
Cow	Iron Age	1	-21.8	-	-21.8	-21.8	-21.8	-	6.9	-	6.9	6.9	6.9	-
	Roman	9	-21.7	0.2	-21.7	-22.0	-21.1	0.9	6.5	0.7	6.7	5.1	7.2	2.1
	Early Saxon	4	-21.6	0.5	-21.5	-22.3	-21.2	1.1	6.8	0.4	6.8	6.4	7.2	0.8
	Middle Saxon	6	-21.7	0.3	-21.6	-22.1	-21.3	0.8	6.9	1.0	7.0	5.3	8.1	2.8
	Late Saxon	5	-21.5	0.4	-21.4	-22.0	-21.0	1.0	6.9	0.9	6.6	6.0	7.9	1.9
	High Medieval	5	-21.6	0.5	-21.4	-22.5	-21.2	1.3	6.9	1.1	7.1	5.5	8.3	2.8
	Late Medieval	20	-21.7	0.4	-21.6	-22.4	-21.1	1.3	7.6	1.6	7.8	5.0	10.1	5.1
	Post-Medieval	8	-21.7	0.4	-21.8	-22.4	-20.9	1.5	7.4	2.3	7.1	4.5	11.3	6.8
Horse	Iron Age	1	-22.4	-	-22.4	-22.4	-22.4	-	4.9	-	4.9	4.9	4.9	-
Pig	Roman	7	-21.3	0.2	-21.5	-21.5	-20.9	0.6	10.1	1.5	11.0	7.4	11.4	4.0
	Early Saxon	5	-21.2	0.7	-21.5	-22.0	-20.5	1.5	7.4	1.5	6.8	6.0	9.4	3.4
	Middle Saxon	6	-21.5	0.5	-21.3	-22.5	-21.0	1.5	8.8	1.3	9.3	7.1	10.1	3.0
	Late Saxon	5	-21.2	0.4	-21.3	-21.7	-20.7	1.0	7.3	0.9	7.0	6.6	8.9	2.3
	High Medieval	5	-21.1	0.6	-21.0	-22.1	-20.4	1.7	8.0	1.3	8.6	6.2	9.3	3.1
	Late Medieval	20	-21.0	0.5	-21.0	-21.8	-20.5	1.3	8.1	1.7	8.6	4.5	11.5	7.0
	Post-Medieval	8	-20.5	0.6	-20.8	-21.2	-19.6	1.6	8.5	3.4	9.2	4.7	13.9	9.2
Sheep	Iron Age	2	-21.8	0.3	-21.8	-22.0	-21.6	0.4	6.5	0.9	6.5	5.9	7.1	1.2

Taxon	*Period*	*n*	**Bone Collagen $\delta^{13}C$ (‰) (VPDB)**						**Bone Collagen $\delta^{15}N$ (‰) (AIR)**					
			Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
	Roman	9	-21.6	0.7	-21.7	-22.7	-20.4	2.3	6.7	1.2	6.3	5.1	8.6	3.5
	Early Saxon	5	-21.8	0.5	-21.9	-22.1	-21.0	1.1	7.1	0.5	7.1	6.4	7.8	1.4
	Middle Saxon	5	-21.7	0.5	-21.9	-22.2	-21.1	1.1	7.5	0.8	7.2	6.9	8.7	1.8
	Late Saxon	5	-21.6	0.3	-21.6	-21.9	-21.2	0.7	6.4	0.5	6.3	5.9	7.0	1.1
	High Medieval	5	-21.5	0.5	-21.4	-22.1	-20.8	1.3	7.0	1.7	7.3	5.0	9.3	4.3
	Late Medieval	20	-21.8	0.4	-21.8	-22.8	-20.8	2.0	8.1	1.1	8.0	5.6	10.3	4.7
	Post-Medieval	8	-21.7	0.6	-21.4	-22.6	-21.1	1.5	8.9	1.8	8.5	7.2	12.9	5.7
TOTAL		**252**												
[Herbivores- combined cow and sheep/goat values]	Iron Age	3	-21.8	0.2	-21.8	-22.0	-21.6	0.4	6.6	0.7	6.9	5.9	7.1	1.2
	Roman	18	-21.6	0.5	-21.7	-22.7	-20.4	2.3	6.6	1.0	6.6	5.1	8.6	3.5
	Early Saxon	9	-21.7	0.4	-21.8	-22.3	-21.0	1.3	7.0	0.4	7.1	6.4	7.8	1.4
	Middle Saxon	11	-21.7	0.4	-21.7	-22.2	-21.1	1.1	7.2	0.9	7.2	5.3	8.7	3.4
	Late Saxon	10	-21.5	0.3	-21.5	-22.0	-21.0	1.0	6.7	0.7	6.5	5.9	7.9	2.0
	High Medieval	10	-21.5	0.5	-21.4	-22.5	-20.8	1.7	7.0	1.3	7.2	5.0	9.3	4.3
	Late Medieval	40	-21.7	0.4	-21.7	-22.8	-20.8	2.0	7.9	1.4	7.9	5.0	10.3	5.3
	Post-Medieval	16	-21.7	0.5	-21.7	-22.6	-20.9	1.7	8.2	2.2	7.9	4.5	12.9	8.4

Table 62: Summary statistics for bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from all Cambridgeshire fauna (excluding fish) analysed, by British archaeological/cultural period. High/Late Medieval data highlighted in grey.

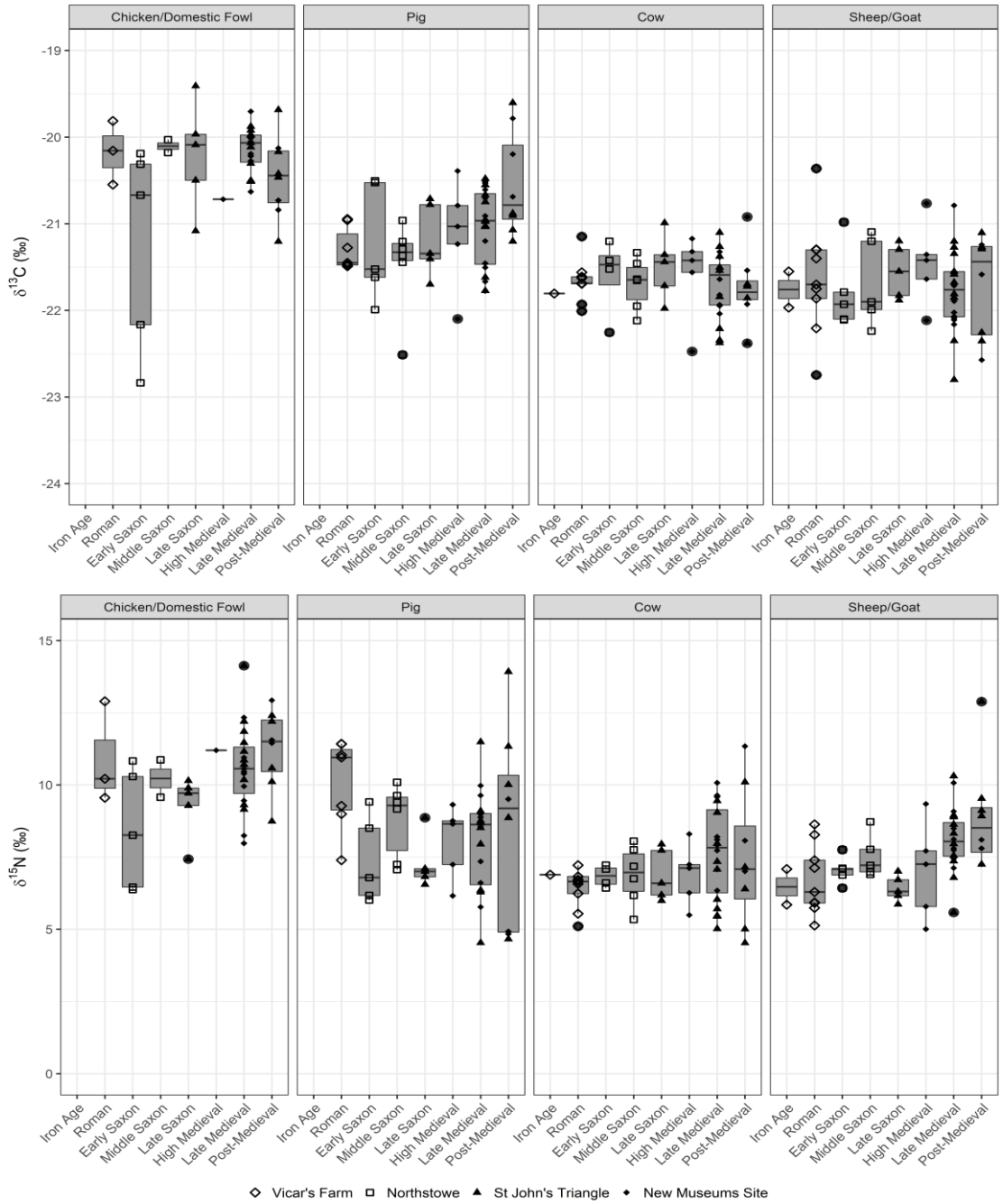


Figure 116: Boxplots showing bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for domestic fauna analysed from Cambridgeshire sites, by British archaeological/ cultural period

8.2 Human-Faunal Offset Calculations

The human-faunal offset was estimated by calculating the mean herbivore (cow and sheep/goat) $\delta^{13}C$ and $\delta^{15}N$ values for each British archaeological/cultural period and subtracting this value from each human $\delta^{13}C$ and $\delta^{15}N$ value in the corresponding period, creating human-faunal offset Δ isotope values (following previous approaches e.g. by Lightfoot *et al.* 2012, 2015, Müldner 2013). Individuals with broad, non-specific date estimates were not included. Cow and sheep/goat were chosen for the baseline as they were commonly consumed by humans in the past (Woolgar 2006a) (see Chapter 2) and, as they are herbivores, they allow for estimations of trophic level when compared to the human data. The cow and sheep/goat values were pooled together so that their $\delta^{13}C$ and $\delta^{15}N$ values were broadly representative of the herbivore protein available to the general population. However, while this is a more comprehensive baseline sample than most isotope studies, the faunal bone was still only sourced from a limited number of sites and may not be directly representative of the food sources of the humans analysed.

Figure 117 and Figure 118 show the herbivore $\delta^{13}C$ and $\delta^{15}N$ values through time, as well as the 'raw' and offset rib and dentine collagen values to illustrate how the offset has considerably altered the relationships in the data (see Appendix III for 'raw' data and further plots). The estimated predator-prey trophic level enrichment range of 0-2‰ for $\delta^{13}C$ (Bocherens and Drucker 2003) and a wide estimate of 3-6‰ for the typical ^{15}N offset between human collagen and diet has been added to figures with offset values (Bocherens and Drucker 2003, Hedges and Reynard 2007, O'Connell *et al.* 2012). It is assumed that a mixed diet will produce offset values within these ranges and values substantially above or below this could indicate marine protein consumption, unusually high or low animal protein consumption, or metabolic disturbance (see Chapter 3 for more detail). Almost all offset values are towards the upper half of this $\delta^{13}C$ range (1-2‰), or above, indicating isotope enrichment over the main 'prey' of the Cambridge individuals (Figure 117). The IQR for almost all offset values are within the estimated range for the typical ^{15}N offset, but a number of individuals do fall above and below, perhaps indicating differential access to animal proteins or marine food sources (Figure 118). Alternatively, it could indicate that the assumptions and data used to create the human-faunal offset values were not appropriate.

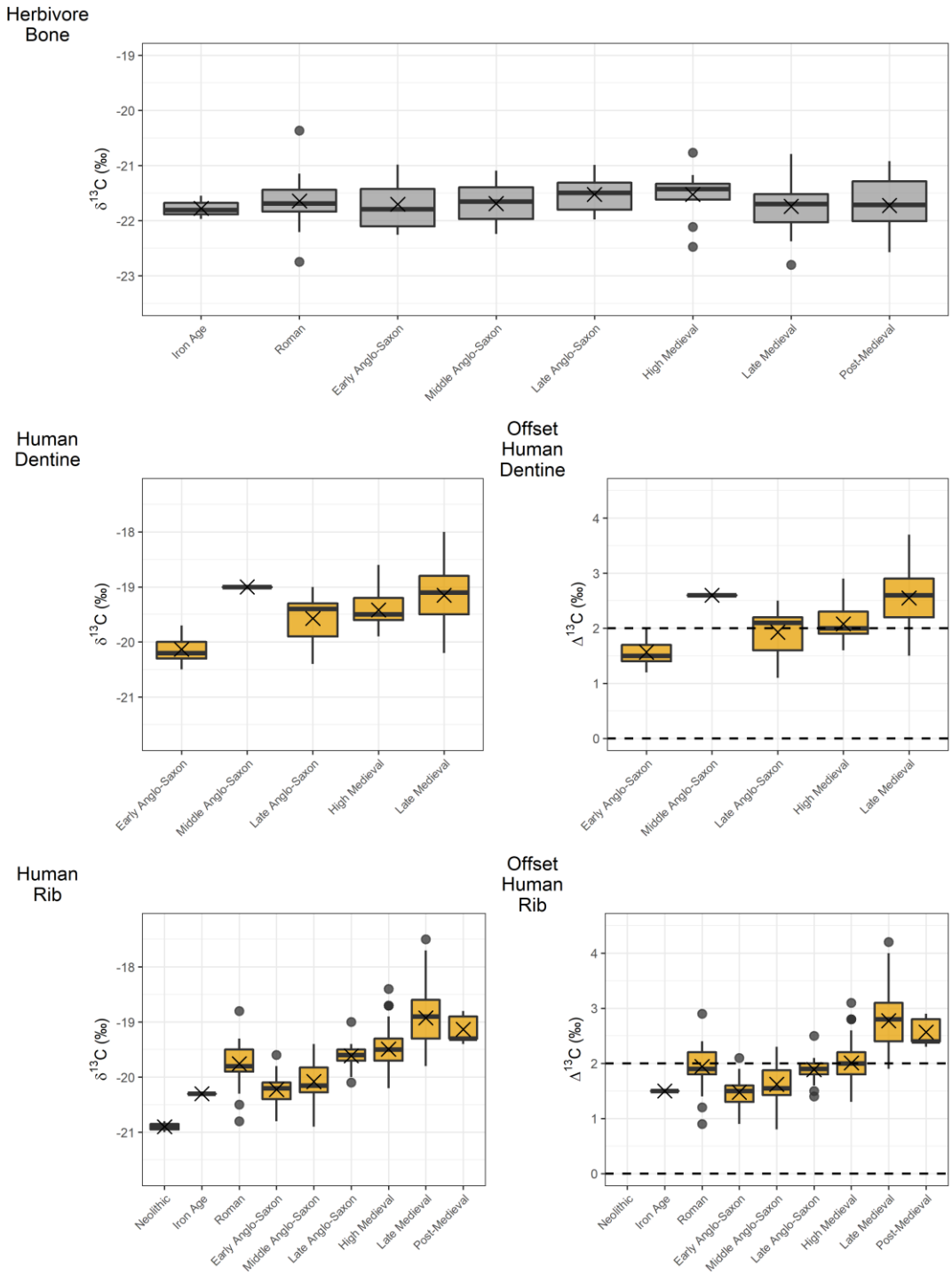


Figure 117: Boxplots showing herbivore (cow and sheep/goat) bone collagen $\delta^{13}C$ values, human dentine and rib collagen $\delta^{13}C$ values and human-faunal offset $\Delta^{13}C$ values for all adult Cambridgeshire individuals who were assigned to a British archaeological/cultural period.
Offset values are not absolute. Dashed lines indicate typical equivalent to one full trophic level effect $\Delta^{13}C$ range of 0-2‰ (Bocherens and Drucker 2003)

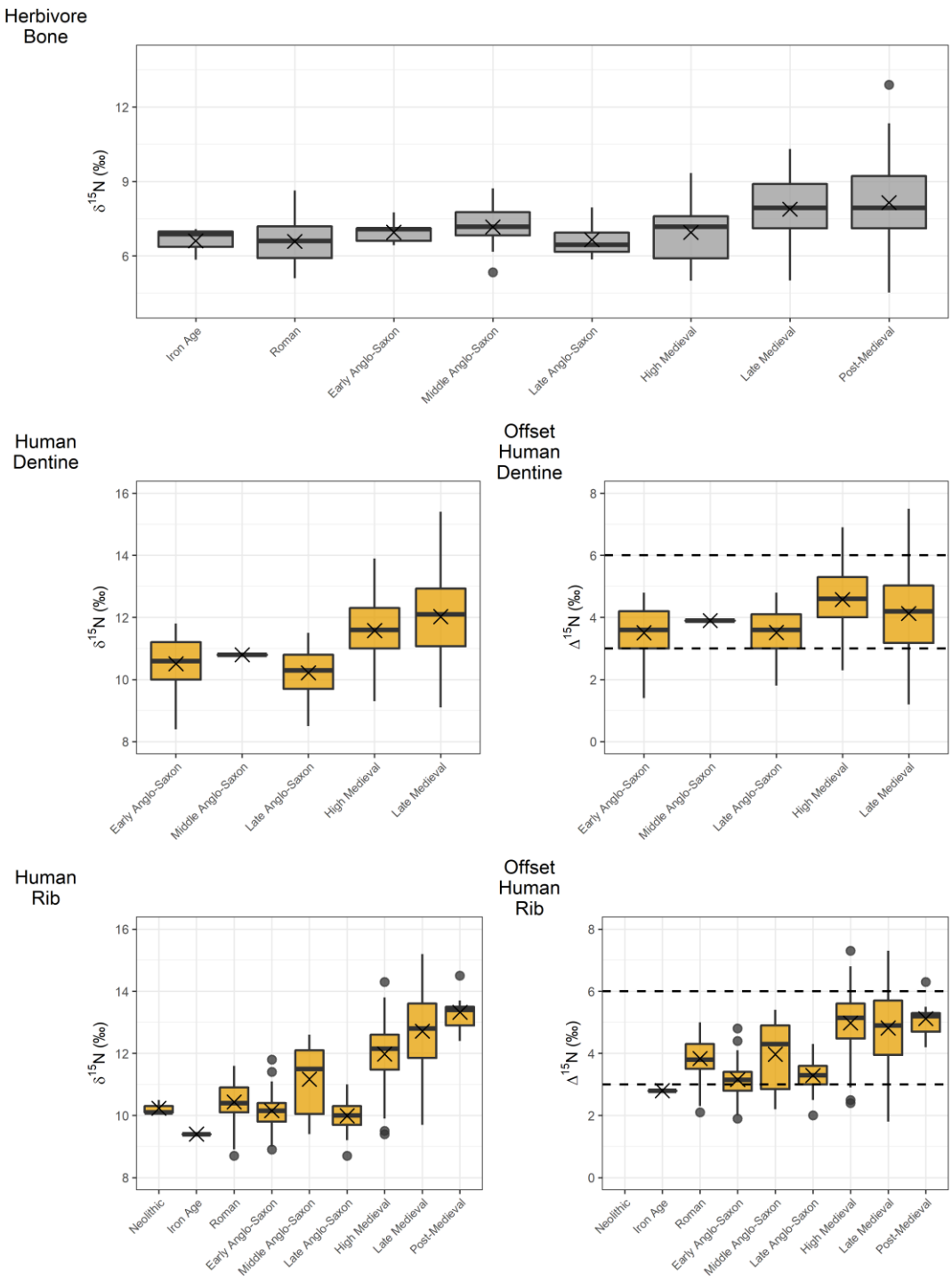


Figure 118: Boxplots showing herbivore (cow and sheep/goat) bone collagen δ15N values, human dentine and rib collagen δ15N values and human-faunal offset ⊿15N values for all adult Cambridgeshire individuals who were assigned to a British archaeological/cultural period.
Offset values are not absolute. Dashed lines indicate typical human-faunal offset ⊿15N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

8.3 Longue Durée Human Isotope Results

There are considerable changes across the longue durée in most of the isotopes analysed. This is largely to be expected considering the large number and type of sites analysed, although despite the large amount of data, some time periods are still represented by one site only, which may not be representative of the chronological period. This is particularly apparent in the Middle Anglo-Saxon (MA-S), where the unusual values from the high-status site of Westfield Farm (Lucy *et al.* 2009) are unlikely to be typical of a Middle Saxon isotope signature.

A general trend in increasing mean dentine $\Delta^{13}C$ values from the Early Anglo-Saxon (EA-S) to the Late Medieval period is present, excluding the one M-AS individual (Table 63, Figure 119). The $\Delta^{13}C$ range is also greatest in the Late Medieval period. The mean rib $\Delta^{13}C$ values increase in the Roman period, followed by a decrease in the EA-S period (Table 64, Figure 120). After this, they follow a similar trend to the dentine, steadily increasing from the E-AS to the Late Medieval period, with an increase of 0.8‰ between the High and Late Medieval periods (Figure 120). Enamel carbonate $\delta^{13}C$ values by longue durée show fluctuations through time, with the lowest mean $\delta^{13}C$ values in the MA-S and the highest in the High Medieval Period, with no meaningful change in mean values between the High and Late Medieval periods (Table 64, Figure 121).

There is no difference in the mean dentine $\Delta^{15}N$ values between the EA-S and LA-S but an increase of 1.1‰ from the LA-S to the High Medieval Period, followed by a decrease in mean $\Delta^{15}N$ values from the High to Late Medieval period (Table 63, Figure 119). The mean rib $\Delta^{15}N$ data fluctuates in the pre-High/Late Medieval periods, with the values from the MA-S (represented by Westfield Farm), being much higher than the E-AS or LA-S which is probably not typical of the general chronological trends in isotope values. Similar to the dentine data, there is a substantial increase of 1.7‰ in mean $\Delta^{15}N$ values between the LA-S and the High Medieval period, but the mean $\Delta^{15}N$ values then plateau, with only a 0.2‰ difference between the High and Late Medieval periods (Table 64, Figure 120).

The $\Delta^{13}C$ and $\Delta^{15}N$ values plotted together show the general trend for similar $\Delta^{15}N$ but differing $\Delta^{13}C$ values between the EA-S and LA-S, followed by an increase in $\Delta^{15}N$ values between the LA-S and High Medieval and similar, or even decreased, $\Delta^{15}N$ values in the Late Medieval

period, but much higher $\Delta^{13}C$ values (Figure 123, Figure 124) This evidence attests to large changes in diet between the Early Medieval (Anglo-Saxon) and High/Late Medieval periods, as well as changes within the High/Late Medieval period. These could be explained by increased consumption of animal proteins and aquatic resources, particularly marine fish in the Late Medieval period (Minagawa and Wada 1984, Schoeninger and DeNiro 1984, Barrett *et al.* 2004, Müldner and Richards 2007b).

The enamel carbonate $\delta^{18}O$ values show fluctuations through time, with the lowest mean $\delta^{18}O$ in the Iron Age and the least negative in the MA-S (Table 66, Figure 122). There is a 0.5‰ difference in the mean $\delta^{18}O$ values for the High and Late Medieval periods, which is larger than between any other time period except the Roman to EA-S at 0.7‰. The MA-S period had the widest range of values, but this is driven by two outliers at Westfield Farm. Aside from the MA-S, the High and Late Medieval period have the widest range of values at 4.5‰ in both periods. Figure 122 illustrates the general overlap in the spread of data from most of the sites, with most having peaks in their density curves around approximately the same values, except the Post-Medieval group whose values are generally lower. High-value outliers are present in both the Roman and MA-S periods and low-value outliers are present in the EA-S, LA-S and High Medieval period, indicating that diversity and 'non-locals' may have been present in most time periods.

Period	*n*	**Dentine Δ^{13}C (‰) (VPDB)**						**Dentine Δ^{15}N (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Early Anglo-Saxon	37	1.6	0.2	1.5	1.2	2.0	0.8	3.5	0.8	3.6	1.4	4.8	3.4
Middle Anglo-Saxon	1	2.6	-	2.6	2.6	2.6	-	3.9	-	3.9	3.9	3.9	-
Late Anglo-Saxon	25	1.9	0.4	2.1	1.1	2.5	1.4	3.5	0.8	3.6	1.8	4.8	3.0
High Medieval	71	2.1	0.3	2.0	1.6	2.9	1.3	4.6	0.9	4.6	2.3	6.9	2.3
Late Medieval	92	2.5	0.5	2.6	1.5	3.7	2.2	4.1	1.4	4.2	1.2	7.5	6.3
TOTAL	**226**												

Table 63: Summary statistics for human-faunal offset dentine collagen ⊿^{13}C and ⊿^{15}N values for Cambridgeshire individuals, by British archaeological/cultural period. High/Late Medieval periods highlighted in light grey

Period	**n**	**Rib Δ^{13}C (‰) (VPDB)**						**Rib Δ^{15}N (‰) (AIR)**					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Iron Age	1	1.5	-	1.5	1.5	1.5	-	2.8	-	2.8	2.8	2.8	-
Roman	53	1.9	0.3	1.9	0.9	2.9	2.0	3.8	0.6	3.8	2.1	5.0	2.9
Early Anglo-Saxon	62	1.5	0.2	1.5	0.9	2.1	1.2	3.2	0.5	3.1	1.9	4.8	2.9
Middle Anglo-Saxon	10	1.6	0.4	1.5	0.8	2.3	1.5	4.0	1.2	4.3	2.2	5.4	3.2
Late Anglo-Saxon	25	1.9	0.2	1.9	1.4	2.5	2.1	3.3	0.5	3.3	2.0	4.3	2.3
High Medieval	84	2.0	0.3	2.0	1.3	3.1	1.8	5.0	0.9	5.1	2.4	7.3	4.9
Late Medieval	139	2.8	0.4	2.8	1.9	4.2	2.3	4.8	1.2	4.9	1.8	7.3	5.5
Post-Medieval	9	2.6	0.3	2.4	2.3	2.9	0.6	5.1	0.6	5.2	4.2	6.3	2.1
TOTAL	**383**												

Table 64: Summary statistics for human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N values for adult Cambridgeshire individuals, by British archaeological/cultural period. High/Late Medieval periods highlighted in light grey

Period	*n*	Enamel Carbonate $\delta^{13}C$ (‰) (VPDB)					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*
Iron Age	1	-12.9	-	-12.9	-12.9	-12.9	-
Roman	55	-13.1	0.7	-13.2	-14.7	-10.9	3.8
Early Anglo-Saxon	38	-14.6	0.5	-14.6	-15.6	-13.6	2.0
Middle Anglo-Saxon	14	-14.9	0.7	-15.0	-15.9	-13.2	2.7
Late Anglo-Saxon	25	-13.0	0.4	-13.0	-13.7	-12.1	1.6
High Medieval	74	-12.7	0.6	-12.7	-14.5	-11.4	3.1
Late Medieval	121	-12.8	0.5	-12.7	-15.1	-11.7	3.4
Post-Medieval	4	-13.3	0.5	-13.3	-13.9	-12.7	1.2
TOTAL	**332**						

Table 65: Summary statistics for tooth enamel carbonate $\delta^{13}C$ values for Cambridgeshire individuals, by British archaeological/cultural period.

Period	*n*	Enamel Carbonate $\delta^{18}O$ (‰) (VPDB)						*Enamel Phosphate $\delta^{18}O$ (‰) (VSMOW) (Chenery 2012 eq.)*					
		Mean	*SD*	*Median*	*Min*	*Max*	*Range*	*Mean*	*SD*	*Median*	*Min*	*Max*	*Range*
Iron Age	1	-6.3	-	-6.3	-6.3	-6.3	-	15.5	-	15.5	15.5	15.5	-
Roman	55	-5.6	0.8	-5.7	-7.1	-3.2	3.9	16.2	0.9	16.1	14.7	18.8	4.1
Early Anglo-Saxon	38	-4.9	0.6	-4.9	-6.4	-3.5	2.9	17.0	0.6	17.0	15.4	18.5	3.1
Middle Anglo-Saxon	14	-4.7	1.5	-4.8	-6.5	-1.9	4.6	17.1	1.5	17.1	15.2	19.9	4.7
Late Anglo-Saxon	25	-5.0	0.6	-5.1	-6.6	-3.9	2.7	16.8	0.7	16.8	15.2	18.1	2.9
High Medieval	74	-5.3	1.0	-5.3	-8.0	-3.5	4.5	16.6	1.0	16.6	13.7	18.5	4.8
Late Medieval	121	-4.8	0.8	-4.8	-6.9	-2.4	4.5	17.1	0.9	17.1	14.9	19.6	4.7
Post-Medieval	4	-6.2	0.9	-6.5	-6.9	-4.9	2.0	15.6	1.0	15.3	14.9	17.0	2.1
TOTAL	**332**												

Table 66: Summary statistics for tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for Cambridgeshire individuals, by British archaeological/cultural period. High/Late Medieval periods are highlighted in light grey.

Dentine Collagen $\Delta^{13}C$ and $\Delta^{15}N$

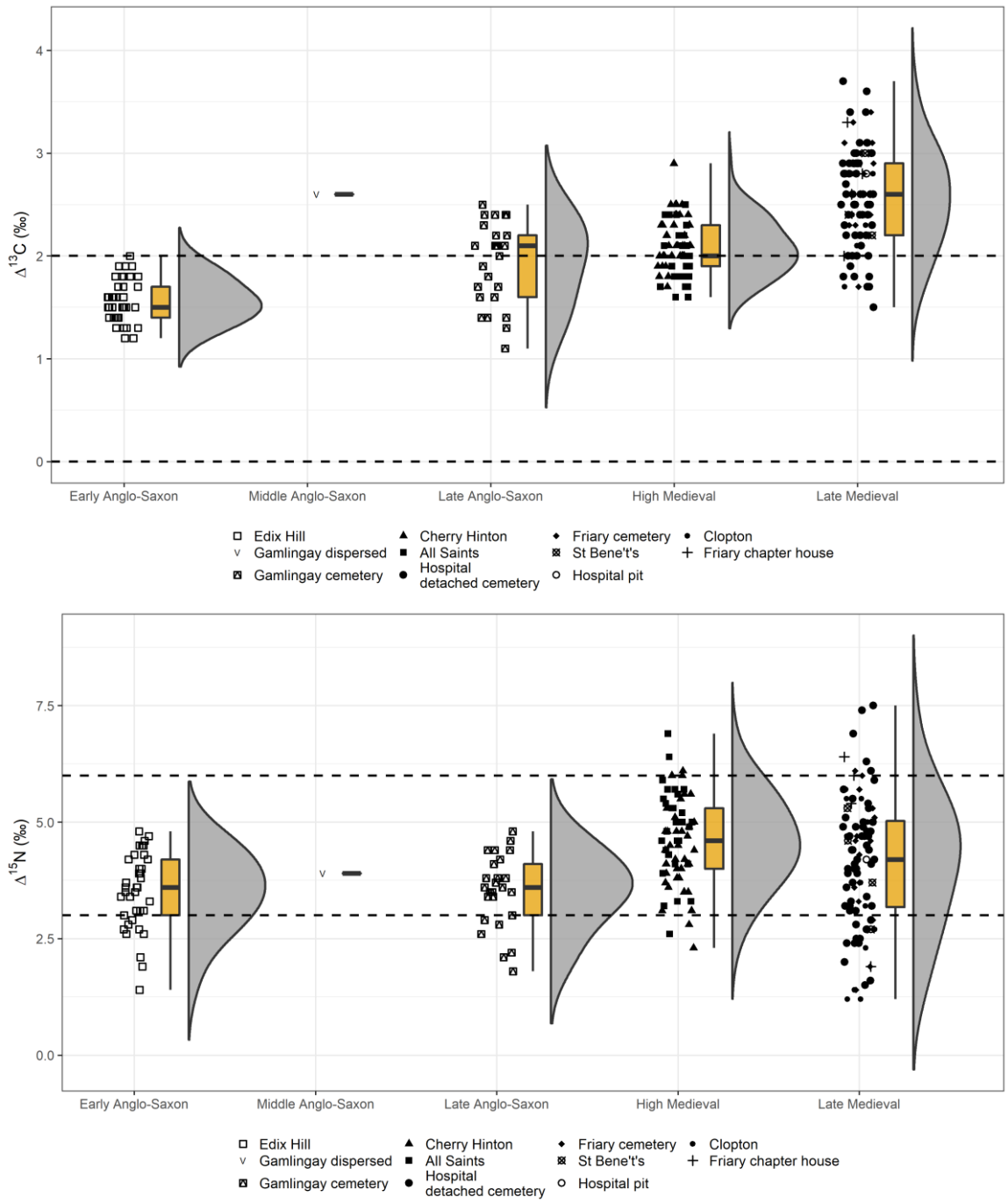


Figure 119: Raincloud plots showing human-faunal offset dentine collagen ⊿^{13}C and ⊿^{15}N values for all Cambridgeshire individuals who were assigned to a British archaeological/cultural period.
Offset values are not absolute. Dashed lines indicate typical equivalent to one full trophic level effect ⊿^{13}C range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

Rib Collagen $\Delta^{13}C$ and $\Delta^{15}N$

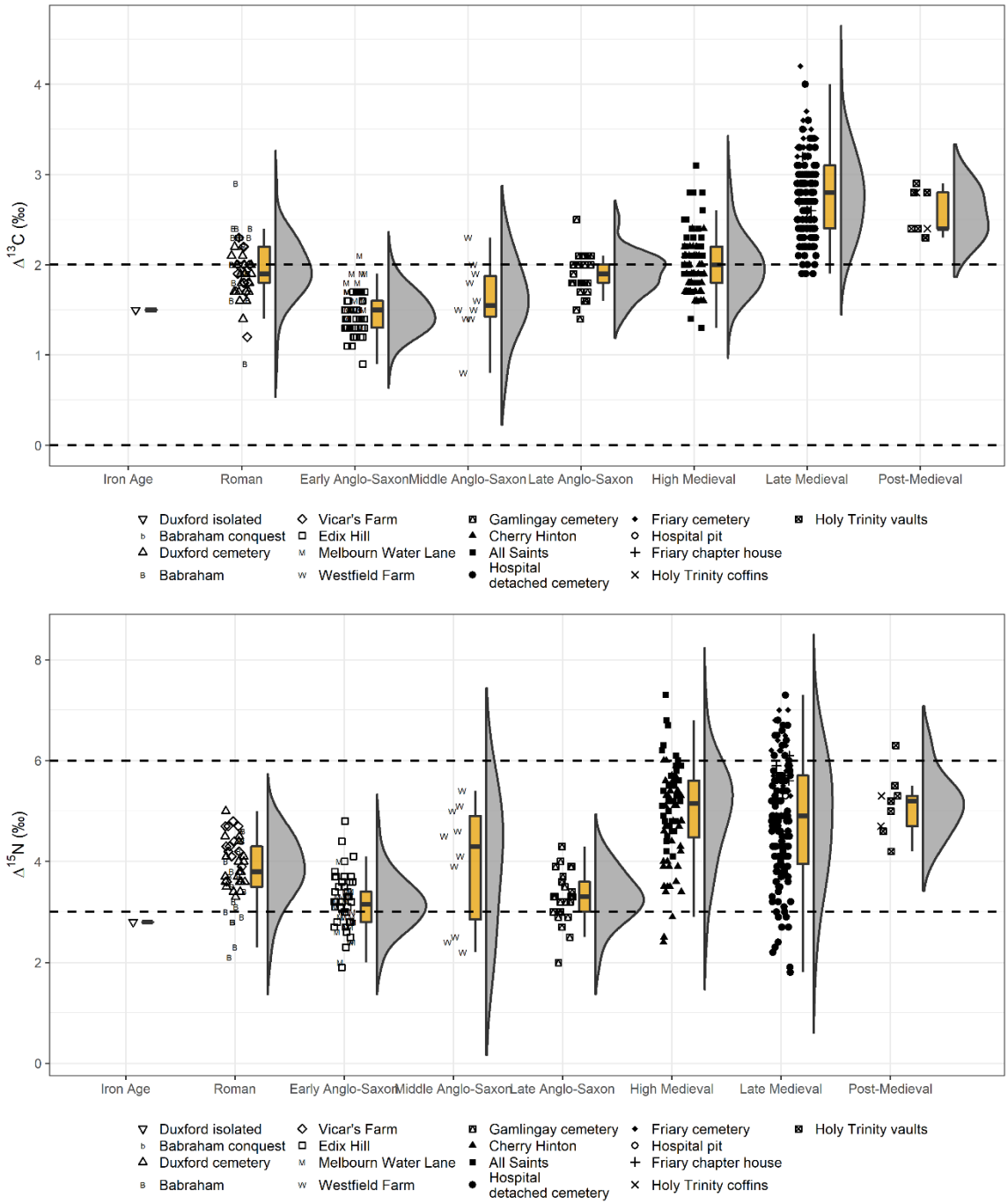


Figure 120: Raincloud plots showing human-faunal offset rib collagen $\Delta^{13}C$ and $\Delta^{15}N$ values for all adult Cambridgeshire individuals who were assigned to a British archaeological/ cultural period.
Offset values are not absolute. Dashed lines indicate typical equivalent to one full trophic level effect $\Delta^{13}C$ range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset $\Delta^{15}N$ range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

Enamel Carbonate $\delta^{13}C$ and $\delta^{18}O$

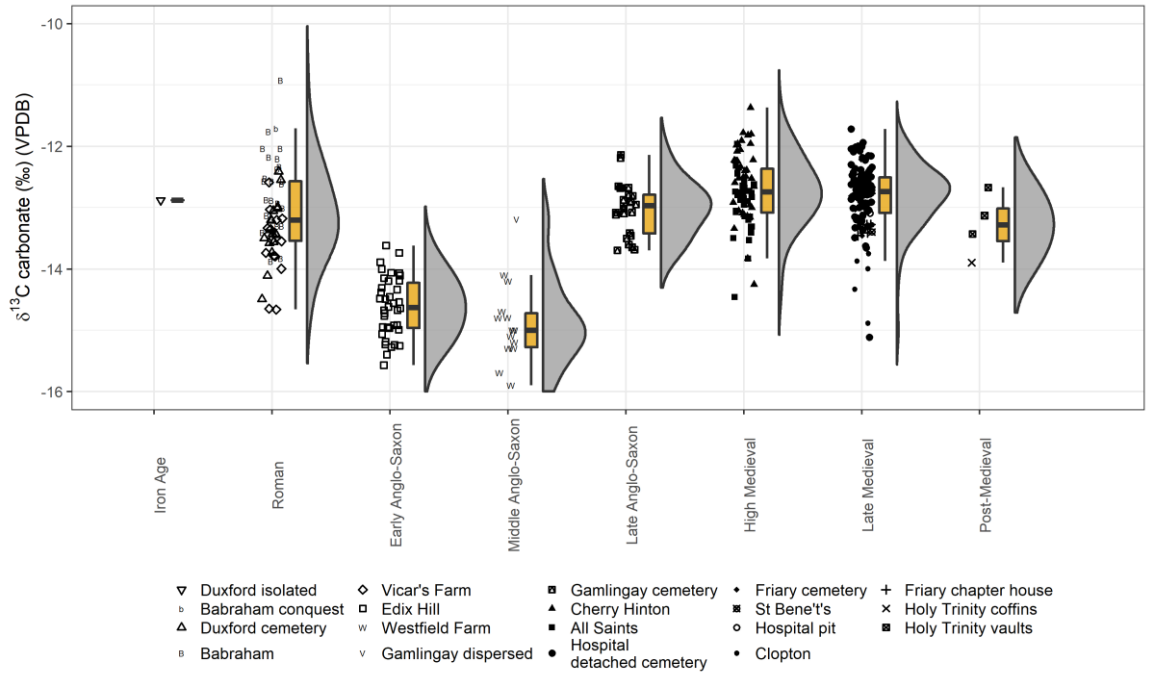


Figure 121: Raincloud plot showing tooth enamel carbonate $\delta^{13}C$ values for all Cambridgeshire individuals who were assigned to a British archaeological/ cultural period, by site subgroup

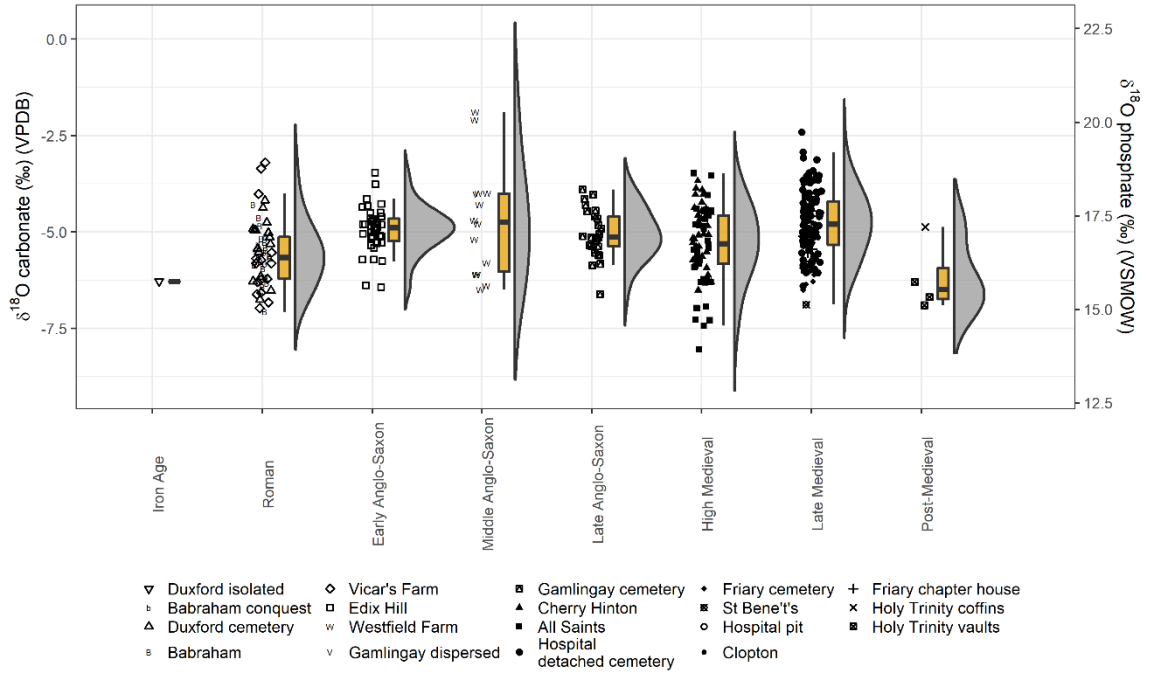


Figure 122: Raincloud plot showing tooth enamel carbonate $\delta^{18}O$ (and converted phosphate $\delta^{18}O$) values for all Cambridgeshire individuals who were assigned to a British archaeological/ cultural period, by site subgroup

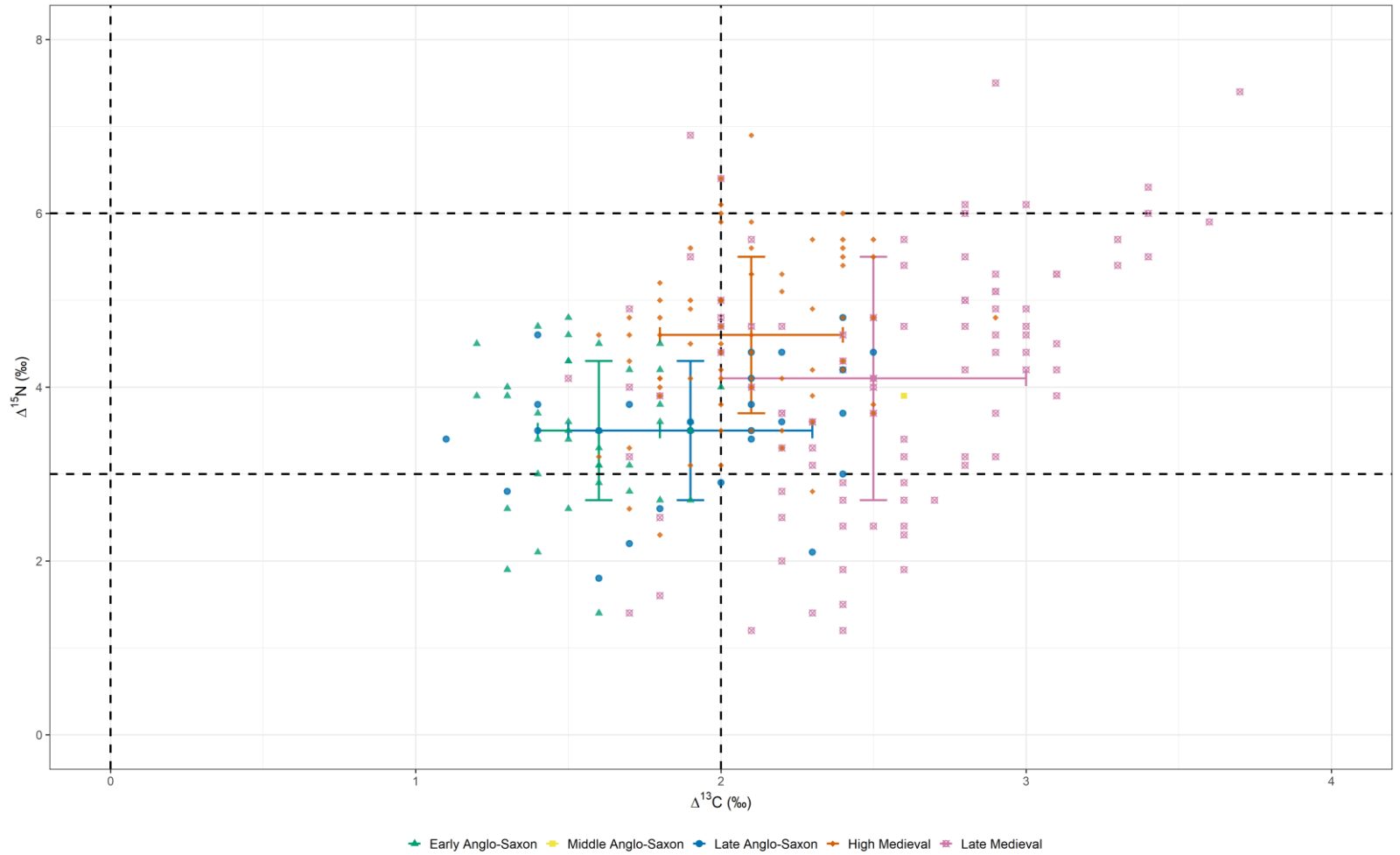


Figure 123: Scatterplot showing mean and individual human-faunal offset dentine collagen ⊿^{13}C and ⊿^{15}N values for all Cambridgeshire individuals who were assigned to a British archaeological/ cultural period. Error bars indicate 1 SD from the mean.
Offset values are not absolute. Dashed lines indicate typical equivalent to one full trophic level effect ⊿^{13}C range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

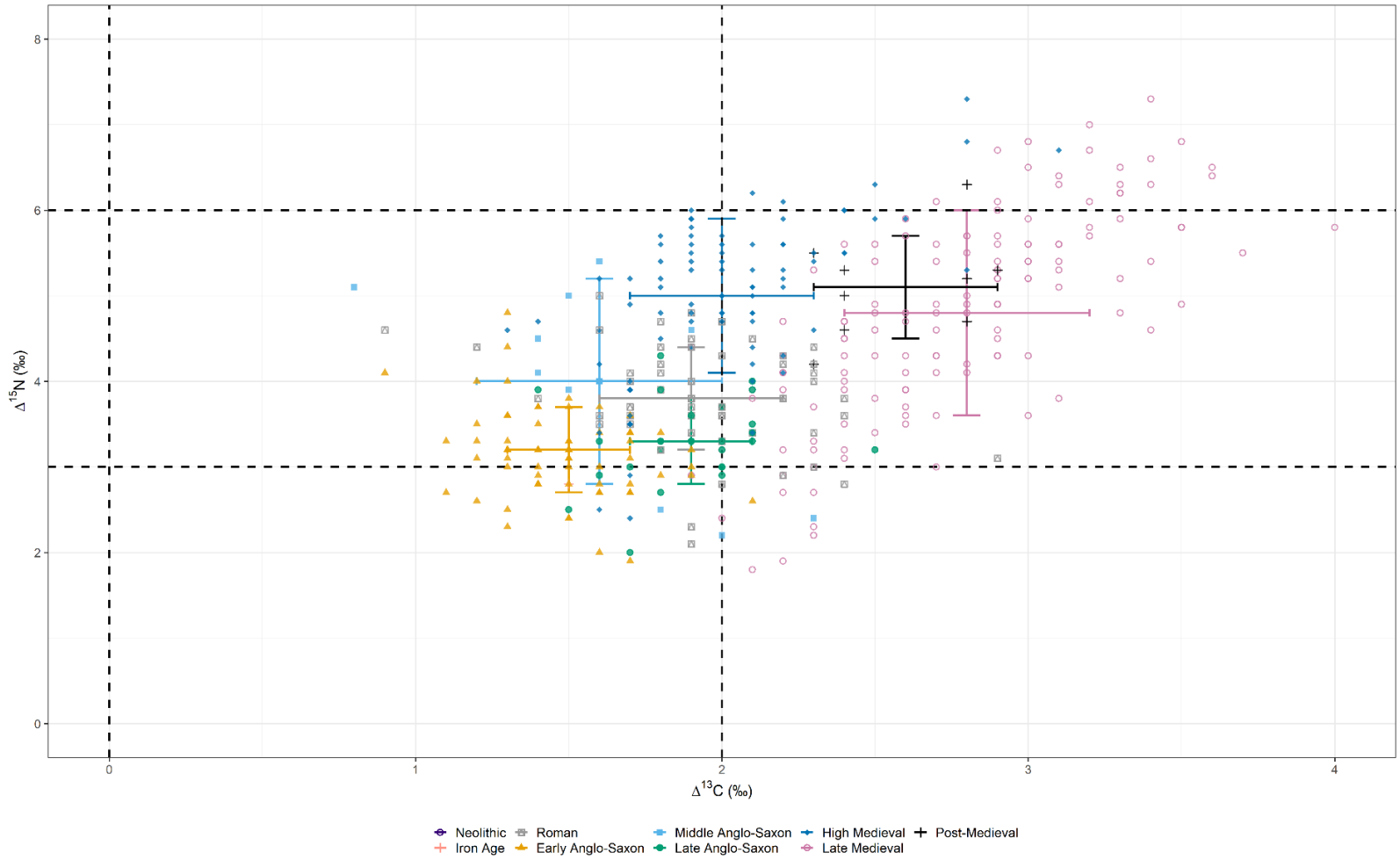


Figure 124: Scatterplot showing mean and individual human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N values for all Cambridgeshire individuals who were assigned to a British archaeological/ cultural period. Error bars indicate 1 SD from the mean.
Offset values are not absolute. Dashed lines indicate typical equivalent to one full trophic level effect ⊿^{13}C range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

8.3.1 Statistical Testing: Longue Durée

Comparisons of the isotope values across the longue durée indicate that all isotopes are unlikely to come from populations with equal means or the same distribution, (one-way ANOVA: enamel carbonate $\delta^{13}C$: p=<0.0001, Kruskal-Wallis test: dentine and rib collagen $\Delta^{13}C$ & $\Delta^{15}N$, enamel carbonate $\delta^{13}C$: all p-values= <0.0001), which is unsurprising considering the large dataset comprising of many sites.

Post-hoc tests show a substantial number of pairwise comparisons that indicate differences between time periods (see Appendix VI). This corroborates the results of the explorative analysis above that there is considerable variation in the distribution of isotopic signatures through time, particularly for adult rib collagen $\Delta^{13}C$, where 12 pairwise comparisons produced *p.adj* values <0.05. Pairwise comparisons between High and Late Medieval groups produced *p.adj* values <0.05 for all carbon isotope values but not nitrogen, pairwise comparisons also confirm substantial changes in the distribution of $\Delta^{15}N$ values between the LA-S and High Medieval period. For enamel carbonate $\delta^{18}O$, pairwise comparisons between the Roman and EA-S, Roman and Late Medieval and High Medieval and Late Medieval have *p.adj* values <0.05.

8.4 Summary of Longue Durée Isotope Results

This chapter has explored the results of human and faunal isotope analysis, spanning the Neolithic to the Post-Medieval period, in order to quantify changes across the longue durée and place the High/Late Medieval data into a wider context.

The faunal data in Section 8.1 shows faunal isotope values change considerably through time for all species, potentially indicating changes in husbandry practices.

Section 8.2 implemented human-faunal offset values to analyse the isotope data across the longue durée. This probably represents one of the most substantial temporally and spatially appropriate faunal isotopic baselines used in an archaeological human isotope study to date. The offsetting demonstrated carbon and nitrogen isotope values within or above the typical predator-prey trophic level offset (Bocherens and Drucker 2003, Hedges and Reynard 2007, O'Connell *et al.* 2012), indicating most individuals were eating at a trophic level above herbivores and had diets which also contained omnivorous and probably marine proteins.

Section 8.3 demonstrates considerable change in isotope values through time and has placed the High/Late Medieval isotope values in context. This has demonstrated that the High and Late Medieval periods are characterised by generally higher mean and median $\Delta^{13}C$ and $\Delta^{15}N$ values and a much wider range in data, although this is probably partially a product of the larger sample. Importantly, while the longue durée analysis has shown the diversity in the High and Late Medieval periods and the potential differences between them, the largest single difference in consecutive values appears to occur between the Early Medieval (LA-S, MA-S & LA-S) and High/Late Medieval periods, eclipsing changes *within* the High and Late Medieval periods. In light of the evidence discussed in Chapter 2, this could be an indication of the 'fish event horizon' (Barrett *et al.* 2004, 2011).

However, differences in site type, status and geography/geology must be considered when characterising the human and faunal isotopic signature over the longue durée. While there are differences in the isotopic signature by time period, the representation of some time periods is better than others, with the Roman and High/Late Medieval periods being best characterised. The prehistoric periods are very poorly characterised by a very small sample, and the human values for the MA-S are probably also not well characterised by the high status and unusual site

of Westfield Farm. However, the aim of the longue durée analysis was to put the Medieval period into context. In terms of diet, after calculating the human-faunal offset, it is clear that the High and Late Medieval periods are characterised by higher carbon and nitrogen isotope values than previous periods. However, the LA-S is also only characterised by one site subgroup – Gamlingay cemetery, a rural site with indications from the strontium isotope values that it may not be a typical population.

In terms of mobility, this section has demonstrated some differences in human enamel carbonate $\delta^{18}O$ values by British archaeological/cultural time period. The difference in mean values between the High and Late Medieval periods are comparatively large at 0.5‰, although the largest difference between consecutive time periods is 0.7‰ between the Roman and EA-S period. While it is not unreasonable to conclude that this may be indicative of changes in mobility (or food/drink preparation practices) in these periods (Brettell *et al.* 2012, Evans *et al.* 2012, Pederzani and Britton 2019), the geographical differences of the sites that represent the periods should also be acknowledged as a possible cause of variability, particularly as the Early Medieval sites are more widely distributed across Cambridgeshire (particularly Westfield Farm, Ely which is 27km northeast of Cambridge), while the High and Late Medieval sites are largely tightly clustered in Cambridge town centre. Other factors, such as climate change, may also be contributing. The High and Late Medieval periods are characterised by wide ranges in the data (4.5‰), wider than any other time period except the MA-S. However, almost all time periods show ranges close to or above 3.0‰ (Lightfoot and O'Connell 2016), indicating the 'unusually' wide range of $\delta^{18}O$ values in Cambridge is present throughout time, adding weight to the argument that cultural modification or natural underlying reasons are the cause for high levels of variation present in the $\delta^{18}O$ data for the area, rather than consistently high numbers of 'non-locals'. The Roman and MA-S period both have much more convincing high-value outliers than the High and Late Medieval periods and these make more convincing cases for evidence of 'non-locals' than much of the Medieval data, based on $\delta^{18}O$ values alone.

Expanding on the conclusions from Section 7.10, analysis of the isotope data from the longue durée has further demonstrated the difficulty in quantifying changes by time period. This thesis has shown that dividing the Medieval isotope data at AD 1350, or by 13th, 14th and 15th centuries or at c.AD 1272 for the High and Late Medieval periods in the longue durée, leads to different

patterns and interpretations of the results. This exemplifies that in this case, analysing the data by time period is fairly arbitrary and any changes which may be due to the Black Death or other events in the 14th century are difficult to distinguish from other historical changes. Nonetheless, this is an inherent problem present in archaeology and this dataset still represents one of the most high-resolution geographically constrained isotope studies to date.



9. Discussion

This chapter takes the key findings from Chapters 7 and 8 and discusses them in context with information from Chapters 2 and 3, as well as comparative isotope evidence from other studies of High/Late Medieval skeletons from Britain to ascertain the nature of diet and mobility in Medieval Cambridge and what life may have been like in the period. Further information and gazetteers of comparative studies can be found in Appendix IV.

9.1 Fauna and Animal Husbandry in Cambridge

The isotope analysis of the fauna provides contextual information for the human data, but it also reveals information about the fauna itself. It was noted in Chapter 7 that the overall $\delta^{15}N$ values for High/Late Medieval pigs in Cambridgeshire were similar to the herbivores. This was interpreted as the pigs eating a largely plant-based diet. However, when compared to isotope data from other High and Late Medieval sites in Britain the pig values seem to be similar, if not slightly above the mean, to pigs from other studies (e.g. York Fishergate and York Tanner Row (Müldner and Richards 2007b) (Figure 125, Appendix IV). It appears that actually, it is the herbivores which are unusually enriched in ^{15}N. The nitrogen isotope values for Cambridgeshire herbivores are generally higher than comparative sites from the Roman period onwards, particularly in the Late Medieval period, where the mean $\delta^{15}N$ values for Cambridge cows and sheep/goats are 2.0-3.5‰ higher than mean values from Dryslwyn Castle (Millard *et al.* 2013), Dudley Castle (Fisher and Thomas 2012), Newcastle Clavering Place (Kancle *et al.* 2018) and York Fishergate (Müldner and Richards 2007b) (Figure 125, Appendix IV). The Late Medieval cows and sheep/goats from Cambridge have values most similar to those reported from Whithorn Fey Field (although due to their broad dating, these are not plotted in Figure 125)

(Müldner *et al.* 2009), and high $\delta^{15}N$ values were also recorded in domestic herbivores from Portmahomack (Curtis-Summers *et al.* 2014, 2020). At Fey Field and Portmahomack, the high herbivore $\delta^{15}N$ values are attributed to the consumption of halophytic plants which grow on salt marshes, or near the coast (Müldner *et al.* 2009, Curtis-Summers *et al.* 2014, 2020). These can be enriched in ^{15}N compared to other terrestrial plants, which has been shown to greatly increase the $\delta^{15}N$ values for herbivores (Britton *et al.* 2008). The fenland landscape to the north of Cambridge is a dynamic and complex environment (Waller 1990, French 2003, pp. 133–142). During the Medieval period, the northern fenlands around the Wash was comprised of silt fen, whereas the southern fenlands were primarily peat (Ballantyne 2004, Oosthuizen 2017). Some coastal fen areas around the Wash may have provided suitable habitats for halophytic plants (Wheeler 1995) which could, in turn, have resulted in high $\delta^{15}N$ values in livestock grazing in these areas. Although models suggest that a Medieval town like Cambridge may have sourced meat from further afield than its grain supplies (Lee 2003), it is not known whether animals grazed in this area would have been regularly sourced. Therefore, while it is possible that that the high $\delta^{15}N$ values seen in sheep and cow bone excavated from Cambridge are due to halophytic plant consumption from grazing on the coastal silt fens, it may be an unlikely cause of the general trend seen across the herbivores. Wherever the animals were sourced from, the causes of increased $\delta^{15}N$ values in the herbivorous is likely to relate to what they were consuming (DeNiro and Epstein 1981, Minagawa and Wada 1984), indicating high $\delta^{15}N$ values in the soils and/or subsequent grazing and fodder crops – this could have been managed through increased crop manuring (Bogaard *et al.* 2007), an agricultural practice that is known to have been utilised in Late Medieval East Anglia (Campbell and Overton 1993, Stone 2001). Unfortunately, no published isotope data from East Anglian crops is known to be available to further explore this phenomenon.

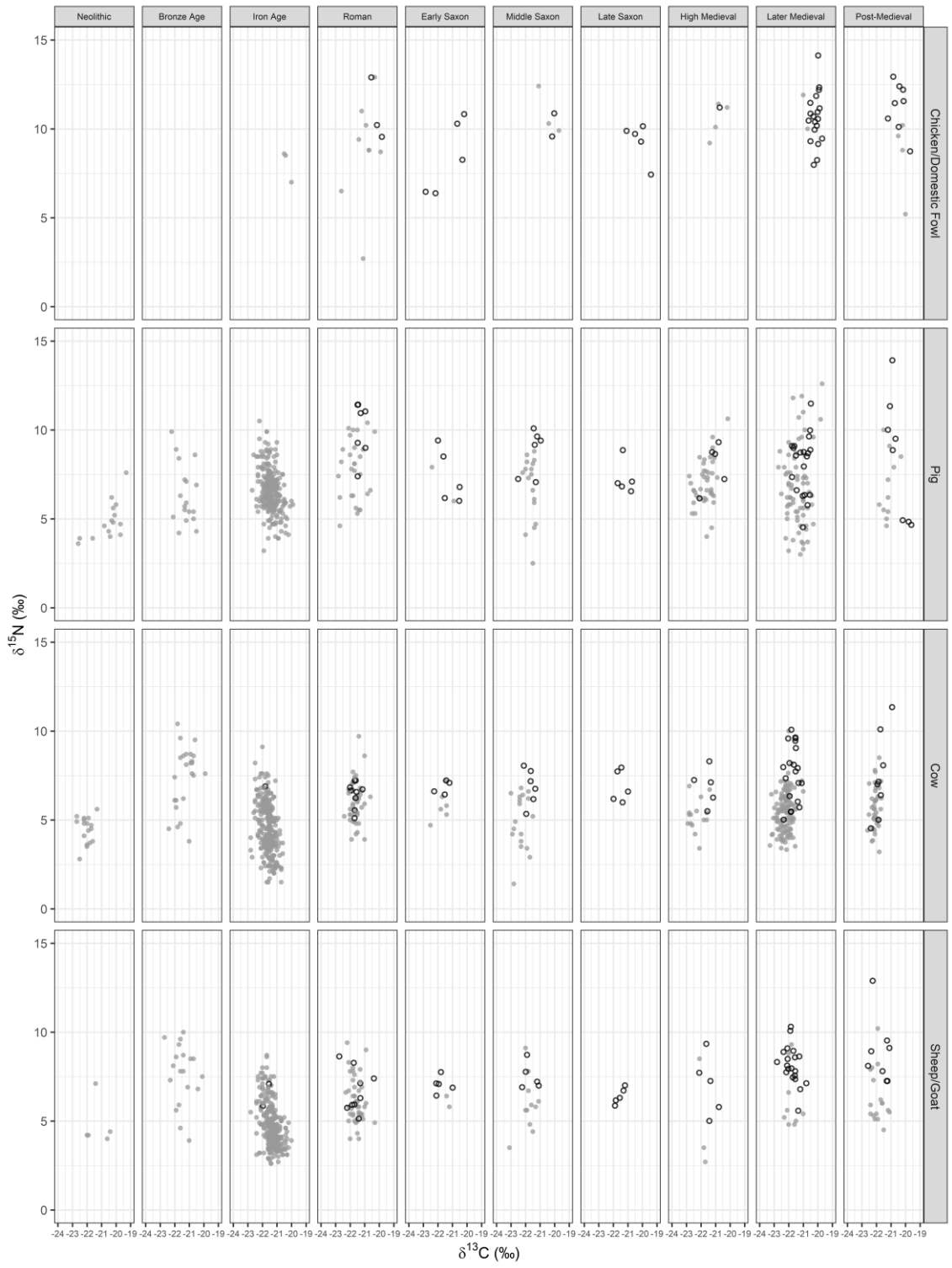


Figure 125: Scatterplots showing Cambridgeshire and comparable bone collagen $\delta^{13}C$ and $\delta^{15}N$ values for domestic terrestrial fauna analysed from British sites, by British archaeological/ cultural period (see Appendix IV for summary data).

Black open circles = Cambridgeshire fauna; Grey circles = comparable British fauna

Historical and archaeological evidence indicates that farming and animal husbandry practices changed over the High and Late Medieval period, with the Black Death commonly being cited as a causative factor (e.g. Stone 2003, 2006, 2012, Albarella 2006, Slavin 2009). The dramatic population decline after the Black Death resulted in less consumers and more available land but also increased labour costs (Campbell *et al.* 1996). Records from demesnes in Norfolk indicate this broadly resulted in a shift to less laborious, extensive mixed practices, with an increased focus on pastoral rather than arable agriculture (*ibid.*). Sheep farming greatly expanded post-1350 (Stone 2003) and chicken husbandry declined in demesnes in East Anglia in favour of production of red meats (Slavin 2009). In contrast, pig management appears to become more intensive in the 14th century, with increased evidence for enclosure (Albarella 2006, Hamilton and Thomas 2012). These changes in agricultural practice may be expected to have an effect on isotope values – changes in arable farming (e.g. types of crops, amount of manuring), may affect isotope values in consumers, and changes in intensity of pastoral farming may also have an effect, both on the absolute isotope values and the range of values (e.g. changes in foddering practice, extensivity of grazing). Isotope studies which have focussed on animal husbandry in Medieval England have reported considerable changes throughout the period. At Dudley Castle, for example, significant changes in pig bone $\delta^{13}C$ and $\delta^{15}N$ values in the 14th century are attributed to changes in pig management after the Black Death (Hamilton and Thomas 2012) and a significant post-Black Death change in $\delta^{13}C$ was also noted in the cattle bone sampled, which was potentially attributed to changes in crop management (Fisher and Thomas 2012). In general, by taxa, the terrestrial fauna from Cambridgeshire do show differences in $\delta^{15}N$ values pre- and post-1350 and across the longue durée, indicating that husbandry and/or farming practices changed through time. The chickens/domestic fowl and pigs both show an increase in $\delta^{15}N$ post-1350 which may be attributed to changes from extensive to intensive husbandry practices. Keeping animals in a more controlled, urban environment where they had more access to a diet containing animal proteins, such as domestic food waste, could account for higher $\delta^{15}N$ values (Albarella 2006, p. 86). Archaeological evidence suggests chickens and pigs were reared in Cambridge throughout the High/Late Medieval period, but perhaps people increasingly ate 'urban' meat in the later periods.

The overall isotope values for fish from Cambridgeshire are similar to those from other High/Late Medieval sites. The majority of the suitable comparative data comes from Beverley

Dominican Priory (Müldner and Richards 2005), Coppergate, York (Barrett *et al.* 2011), Fishergate, York (Müldner and Richards 2007b) and various sites in London (Barrett *et al.* 2011) (see Appendix IV). As might be expected for a diadromous species, there is much more variation in the $\delta^{13}C$ and $\delta^{15}N$ values for eels from Cambridgeshire and the comparative sites but in general they display low $\delta^{13}C$ values compared to most other fish species analysed. In line with studies of freshwater fish (Dufour *et al.* 1999, Fuller *et al.* 2012), the isotope values for cyprinids from Cambridge and comparative sites are quite varied (although the sample size is very small), further highlighting the heterogeneity in potential freshwater fish values and the ongoing difficulty in characterising an archaeological freshwater fish signal. The isotope values for cod sampled from Cambridgeshire sites are similar to the mean values for other High/Late Medieval sites (e.g. Beverley (Müldner and Richards 2005) and York (Müldner and Richards 2007b, Barrett *et al.* 2011)) and are close to values estimated for cod fished from the Southern North Sea (Barrett *et al.*, 2011), indicating this may be the primary source of cod for Cambridge (although the slightly circular nature of this conclusion should be recognised, as archaeological samples from Cambridge were part of the sample used in the paper to characterise the expected value for the Southern North Sea).

9.2 Diet in High/Late Medieval Cambridge

The isotope data generated in this thesis complements the historical accounts and archaeological evidence for High/Late Medieval diet in Cambridge. The range of human $\delta^{13}C$ values are consistent with those expected for a diet containing C_3, rather than C_4 plants (O'Leary 1981, van der Merwe 1991, Pollard *et al.* 2007, Lee-Thorp 2008, Müldner 2009). When combined with the archaeobotanical data (Cessford and Dickens 2019, pp. 119–204, see Section 2.3.1.1), this means that people in Cambridge were likely to be growing and consuming wheat, barley, rye and oats, with no evidence for C_4 plants which may have been available (but not grown) in Britain during the period, such as millet. This was the expected outcome and conforms with other contemporary isotope evidence in Britain (e.g. Müldner and Richards 2005, 2007b, Lakin 2009, Müldner 2009, Britton *et al.* 2015, Bownes *et al.* 2018, Kancle *et al.* 2018) (see Figure 126 below). As discussed in Chapter 2, the historical and archaeobotanical records provide evidence for plants which are invisible to isotope analysis and show that nuts, fruits such as apples and berries, and condiments were consumed and that these were likely

either grown in gardens or purchased at markets and fairs (Cessford and Dickens 2019, pp. 199–204).

In terms of animal protein consumption and trophic level, the High/Late Medieval isotope results are varied, which confirms speculations made in Chapter 2 that factors such as the landscape, location, trade links, fairs and social hierarchies would result in dietary differences in Cambridge. When the human isotope values are offset against the herbivore isotope values (Chapter 8), almost all High and Late Medieval individuals show a trophic level increase over the cows and sheep/goats, indicating they regularly consumed at least some animal protein (Hedges and Reynard 2007, O'Connell *et al.* 2012). The zooarchaeological evidence suggests that beef and mutton were the most commonly consumed meats in Cambridge (Cessford and Dickens 2019, pp. 181–197), however, the high number of individuals who had $\Delta^{15}N$ values well above 3-6‰ means that many individuals must have been eating protein from fauna of a higher trophic level, e.g. pork and chicken, as well as aquatic resources (Schoeninger and DeNiro 1984, Hedges and Reynard 2007, Müldner and Richards 2007b, O'Connell *et al.* 2012) . The high carbon and nitrogen isotope values seen in some individuals, particularly at the Hospital and Friary, indicates marine protein was being consumed by a portion of society (Schoeninger and DeNiro 1984). This pattern has been observed in other Medieval religious institutions in Britain, including bishops from Whithorn Cathedral Priory (Müldner *et al.* 2009) and presumed friars at Newcastle Clavering Place and Northallerton Priory Close (Kancle *et al.* 2018). The isotope data also indicates changes in diet from childhood to adulthood for many individuals, particularly at the urban sites. It appears that most individuals consumed more animal protein in adulthood. For some, this is the result of entering specialist institutions as adults (e.g. the Friary, as seen in Kancle *et al.* (2018)), but for those in the parish sites, the difference in childhood diet may imply that were dietary hierarchies even within families.

Several individuals had dentine and rib collagen $\Delta^{15}N$ values well below 3‰, indicating they were consuming very little animal protein (Hedges and Reynard 2007, O'Connell *et al.* 2012). In total, 25 individuals had rib $\Delta^{15}N$ values below 3‰. Twelve were adults - nine from the Hospital and three from Cherry Hinton. Twenty-four individuals had dentine collagen $\Delta^{15}N$ values below 3‰, representing childhood diet. Unlike for the rib samples, these individuals with low dentine $\Delta^{15}N$ values were present across all the High/Late Medieval sites, although the

majority were from the Hospital. This suggests having very little animal protein in the diet was much more common in non-adults than adults. This could indicate a differentiation or a hierarchy in food provision in family groups, with children being given a diet containing less regular animal proteins. Alternatively, it could highlight the plight of a few unfortunate children who did not have access to adequate nutrition. Whatever the cause, it was present across all sites and so was likely to be ubiquitous in Medieval society. It has been suggested from the isotope analysis at Wharram Percy that High/Late Medieval non-adults between 4-8yr were eating a more plant-based diet than older children or adults (Richards *et al.* 2002). Similarly, at the Medieval Hospital of St Mary Spital, London, it was noted that non-adults aged 6-11yr had lower $\delta^{15}N$ values than adults, although these were rib values from non-survivors (Lakin 2009, p. 161). This repeated finding indicates that non-adults consuming diets low in animal protein may have been a widespread Medieval phenomenon.

Most of the individuals sampled from Cambridgeshire who had low dentine $\Delta^{15}N$ values lived into adulthood and so a childhood diet low in animal protein may not have had a dramatic impact on their later life, however almost all (18/21 observed= 86%) had linear enamel hypoplasia (LEH) in their teeth. LEH have been interpreted as an indication of growth interruption possibly related to environmental stressors during childhood (Hillson 1996, pp. 165–167), indicating that their younger years may have been tough.

Of the 25 individuals with low rib $\Delta^{15}N$ values, the lowest six are all non-adults 7-12yr or 13-17yr, although only one has both rib and dentine values to compare. PSN 1222, an adolescent female from Clopton had both the lowest dentine and rib $\Delta^{15}N$ values, ultimately dying aged 13-17yr. While it may be tempting to attribute her death to food poverty (although not extreme enough to cause starvation (Hobson *et al.* 1993, Mekota *et al.* 2006)), she is actually likely to have died of plague, having tested positive for *Y.pestis* (Scheib in Robb n.d., see Section 2.2.1), giving her an estimated death date between 1349-1400 (Cessford and Alexander in Robb n.d.). This makes her too young to have lived through the Great Famine (Slavin 2016, Alfani and Ó Gráda 2018), but she clearly had little to no animal protein in her diet in the years before her death, indicating perhaps the events preceding the Black Death had badly affected her rural community.

The adults with low rib $\Delta^{15}N$ values were almost exclusively old individuals in the Hospital of St John. This may imply that they may have been too ill to seek out food for themselves and/or unable to afford regular animal protein, as part of their 'deserving poor' status which led to their admission into the Hospital (Rubin 1987). As the historical and isotopic evidence suggests that the diet provided in the Hospital is likely to have contained at least some animal protein (Rubin 1987, Underwood 2008, see Section 2.3.2.1), their low rib $\Delta^{15}N$ values could indicate that they were not in the Hospital for very long before they died or that they were too ill to consume certain foods, for instance, some may have had to have been fed a liquid diet due to dental issues. At the Medieval Hospital of St Mary Spital, London, isotope analysis also highlighted several individuals with low isotope values (Lakin 2009). However, in contrast to the Hospital of St John, these individuals were mostly <35yr. It was hypothesised, but ultimately unproven, that they represented migrants into the area, coming from somewhere which typically consumed less marine protein (Lakin 2009, pp. 163–176). While this scenario cannot be ruled out at the Hospital of St John, given their old age, it is more likely that the former suggestions are the reasons for the lack of animal protein in their diet.

Comparing the isotope data from High/Late Medieval Cambridge to other contemporary studies in Britain puts the data into a wider context and allows for assessments of how typical the diet in Cambridge may have been. In total, there are 21 British sites dating to the High/Late Medieval period with comparable adult rib collagen $\delta^{13}C$ and $\delta^{15}N$ data (see Appendix V for a gazetteer of comparative sites). However, the wide geographical spread of these studies presents problems relating to variable regional isotopic baselines. Therefore, only sites with localised, contemporary herbivore data available to calculate comparable human-faunal offset $\Delta^{13}C$ and $\Delta^{15}N$ values are used here (Figure 126; see Appendix V for a summary of the 'raw' and offset comparative data). Interestingly, calculating and comparing human-faunal offset isotope values for these often-used comparative sites has changed the relative positioning of the mean values in relation to one another. For example, individuals from Portmahomack have by far the highest 'raw' isotope values (Curtis-Summers *et al.* 2014, 2020), but after offsetting, they do not. This is due to elevated $\delta^{15}N$ values in the herbivores at this site and highlights the importance of considering baselines. Offset isotope values from the Cambridgeshire sites seem to sit approximately in the middle of the comparative offset isotope data, indicating that the diet seen at most sites in Cambridge was fairly typical of the period, although they are more similar to

sites from Greater London (e.g. 11: St Mary Spital and 12: St Nicholas Shambles (Lakin 2009)) than Northern England (e.g. 14: Northallerton Priory Close (Kancle *et al.* 2018)) or Scotland (16: Portmahomack (Curtis-Summers *et al.* 2014, 2020) & 23: Whithorn (Müldner *et al.* 2009)) (Figure 126). Many of the sites from Northern England are isotopically distinctive. The combination of high nitrogen but relatively 'terrestrial' carbon isotope values (which are still present after offsetting) has been noted in publications of isotope values from York, suggesting regular consumption of freshwater fish and eels or omnivorous meats such as pork or chicken (Müldner and Richards 2007b, p. 695). This implies that individuals in Cambridge were perhaps not consuming these types of foods as regularly as their Northern counterparts, despite their ready access to eels from the Fens (Lucas *et al.* 1998, Cessford and Dickens 2019, pp. 197–198). The distinction between Cambridge and York, and the similarities between Cambridge and London are even clearer in Figure 127, which compares each town, showing the generally higher $\Delta^{15}N$ values in York (Müldner and Richards 2007a, 2007b, Lakin 2009). Geographically this may make sense as London is closer to Cambridge, but the size and character of the places would have been very different. Although data from two sites cannot characterise a whole city, it is interesting that the spread of data from London is similar to Cambridge, when it was expected that it would have been much more diverse. This is most likely a product of the relative normality/homogeneity of the particular London sites sampled rather than an indication that the population of Cambridge was as diverse as London as a whole.

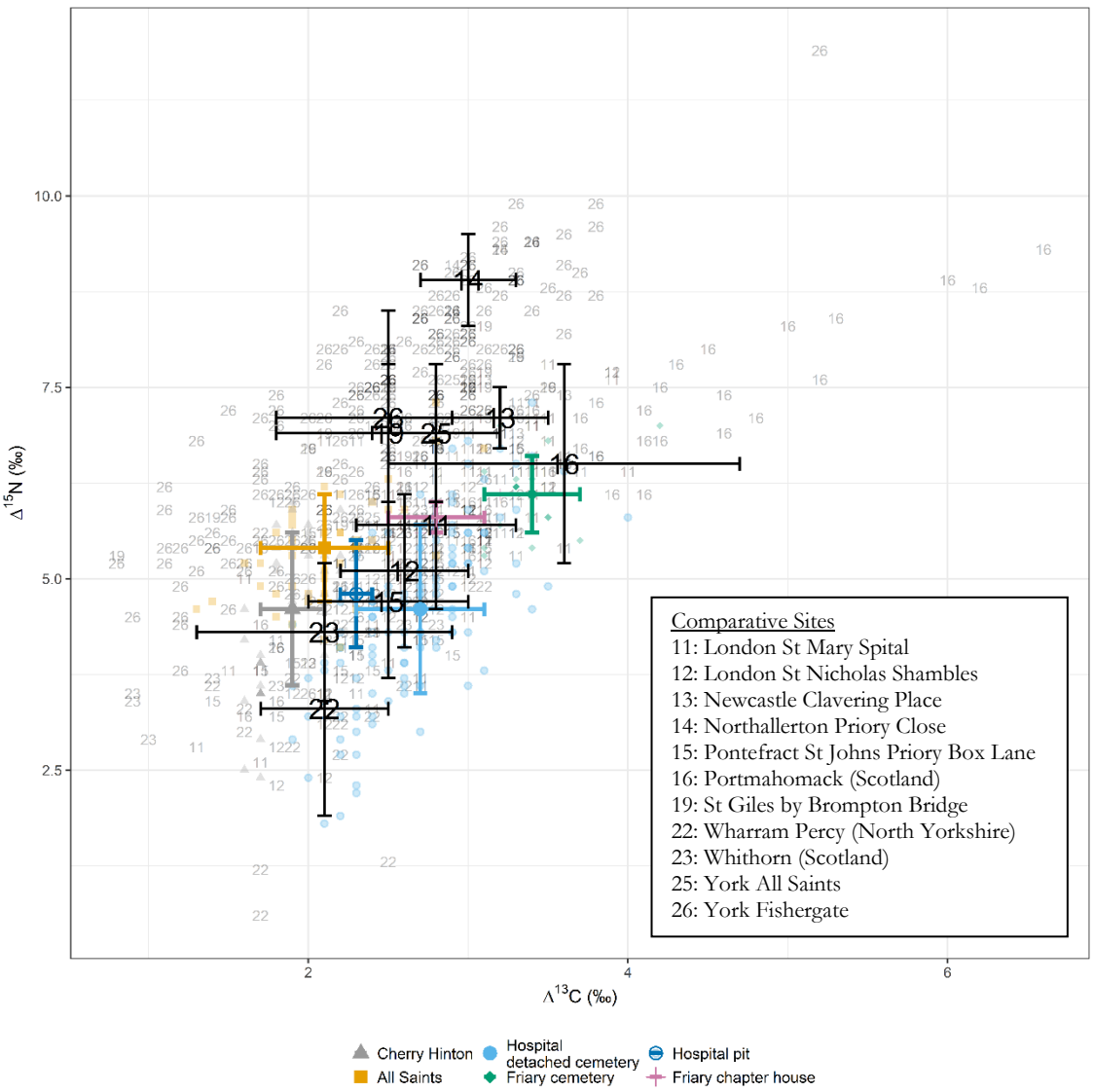


Figure 126: Scatterplots showing mean and individual human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N values for adult High/Late Medieval Cambridgeshire individuals (coloured) and comparative adults from other British High/Late Medieval sites (black), where calculating an offset was possible. Offset values are not absolute. Error bars indicate 1 SD from mean. (see Appendix V for gazetteer of comparative sites).

Site References: 11&12: (Lakin 2009), 13&14: (Kancle et al. 2018), 15: (Bownes et al. 2018), 16: (Curtis-Summers et al. 2014, 2020), 19: (Müldner and Richards 2005, Bownes et al. 2018), 22: (Britton et al. 2015), 23: (Müldner et al. 2009), 25: (Müldner and Richards 2007b), 26: (Müldner and Richards 2007a, 2007b)

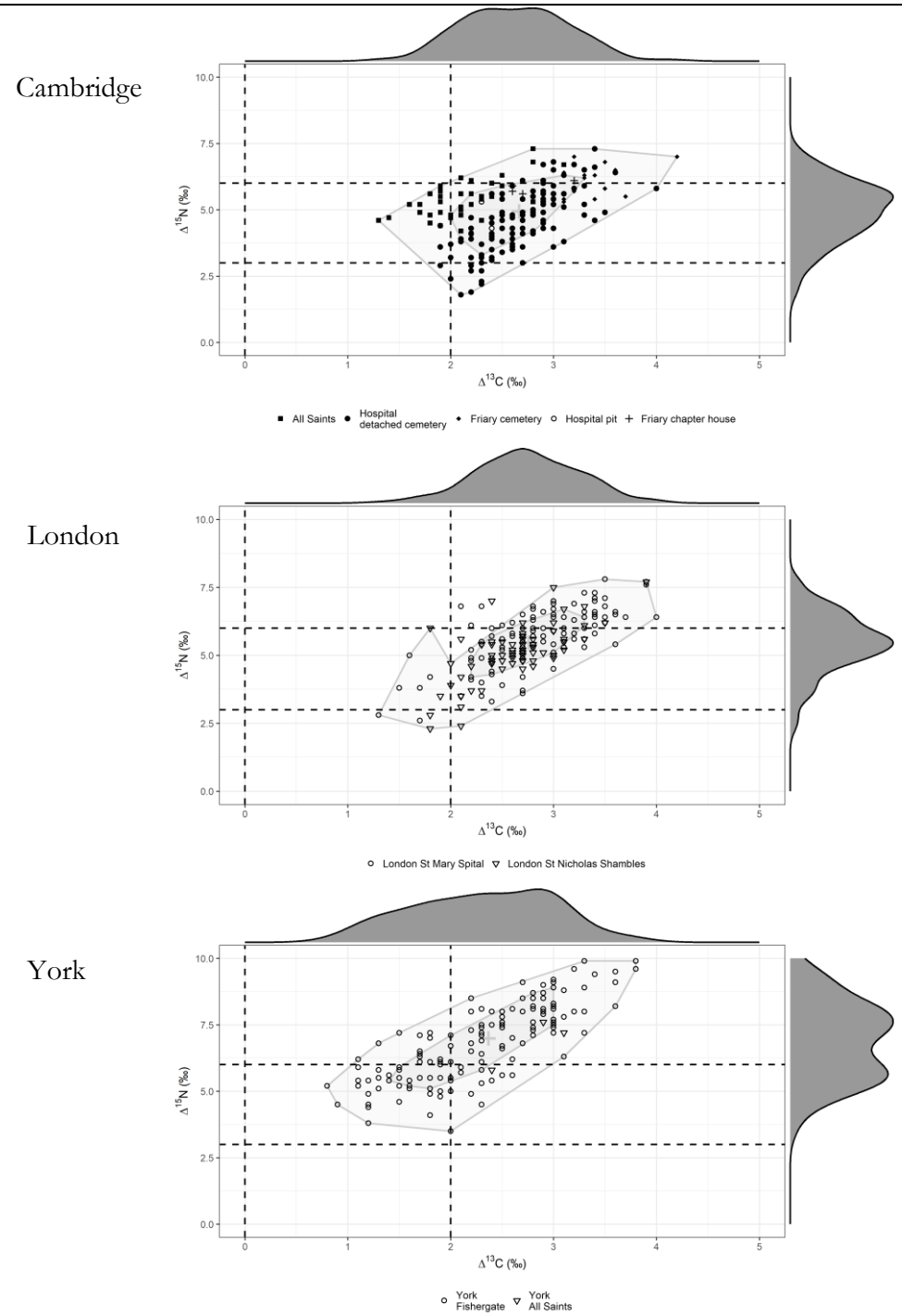


Figure 127: Bagplots with scatterplots (and marginal density) showing human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N for adult High/Late Medieval urban Cambridge individuals and comparative High/Late Medieval adults from London (Lakin 2009) and York (Müldner and Richards 2007a, 2007b) (see Appendix V for more information for comparative sites).
Offset values are not absolute. Dashed black lines indicate typical equivalent to one full trophic level effect ⊿^{13}C offset range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012).

9.2.1 Sex-based Differences in Diet

The evidence discussed in Chapter 2 hinted that there may have been differences in diet between males and females, but was inconclusive (e.g. Bynum 1985, Gilchrist 1999, 2012). Isotope studies of High/Late Medieval sites in Britain have produced mixed results regarding sex-based differences in diet, with most unable to show any meaningful difference in the isotope data by sex, e.g. in London and Hereford (Lakin 2009, Halldórsdóttir *et al.* 2019) and others, such as at Fishergate, York, showing some sex-based differences but ones which cannot be disentangled from temporal or social differences (Müldner and Richards 2007a).

This thesis has shown there is also no convincing evidence of a strong overall sex-based difference in diet in Cambridge and the surrounding areas. However, there are some differences on a site-by-site basis. The Hospital detached cemetery shows the most variation in rib $\delta^{13}C$ and $\delta^{15}N$ values between the sexes. This is hardly surprising, as the Hospital cemetery is likely to contain a wide cross-section of the population (Cessford 2012), leading to a wide range in values. Secular staff at the Hospital may have had a diet less strictly controlled by religious rules (see Section 9.2.2 below) but may have been buried with the inmates (Cessford 2012). Records relating to the identity of the servants at the Hospital indicate they were all male (Rubin 1987, pp. 174–175), which means secular staff buried in the cemetery may contribute to skewing the dietary data by sex. The data from the Hospital does indicate that differences in female and male diet are more pronounced in the 14th century. This may indicate a shift in the types of people admitted to the Hospital or buried in the cemetery, or changes in dietary provisions in the Hospital during this period, but the changes are difficult to interpret.

Adult parish males do appear have a wider range in rib collagen $\delta^{13}C$ and $\delta^{15}N$ values than females. As this could be related to a wider range in access to foodstuffs, particularly terrestrial and marine proteins, this may reflect more layers of social hierarchy present in the male population than female. However, only three or so males have distinctly higher $\delta^{15}N$ values than females and indeed, the lowest $\delta^{15}N$ values in the parish group are also from males, so there is little evidence for regular consumption of greater amounts of meat or feasting behaviours (as suggested by Bynum 1985) in the 'typical' male parish population. In contrast to the town, rural females have slightly higher mean and greater range in both dentine and rib collagen $\delta^{13}C$ and $\delta^{15}N$ values than males. This could indicate that females ate more marine proteins than males

(Schoeninger and DeNiro 1984) or could indicate that rural females were more mobile and came from a more widespread catchment area than males, therefore potentially having more varied dietary practices. PSN 525, one of the only females excavated from the Friary, poses an interesting case (see Robb n.d. for an osteobiography). She was buried in the Chapter House, an area that she would not have been able to enter in life, marking her out as an unusual and likely high-status burial (Cessford 2017, 2020). Her rib collagen isotope values are similar to the males buried in the Chapter House but much higher than the mean values for High/Late Medieval females at any other Cambridgeshire site. She (or someone close to her) must have chosen and paid to be buried in this location which could mark her out as a particularly rich and pious woman. Her isotope values appear to attest to her being high-status, with regular access to animal and marine proteins and do not indicate a person who was regularly restricting their meat consumption, as particularly pious women may have chosen to do (Bynum 1985). However, we cannot rule out other factors which may have affected her isotope values, as her skeleton had multiple active pathologies present at time of death, including potential Paget's disease, whose effects on isotope values are largely unknown.

While there are some sex-based differences in isotope values on a site level, these are nuanced and do not indicate a general, systemic pattern of differential consumption between females and males. Given the growing amount of isotope data which has been unable to conclusively prove a difference in values based on sex alone in the High/Late Medieval period, we can perhaps begin to move to a consensus that if there were any differences in diet, whether due to factors such as feasting behaviours in men, extreme fasting practices in women, or medical recommendations based on the different humours associated with each sex, they were either not a significant occurrence, or at least are largely not detectable by isotope analysis.

The effects of pregnancy on isotope values was discussed in Chapter 3. Although it is unlikely that the effects of pregnancy can be generally observed in archaeological bone collagen, due to issues of bone turnover and confounding dietary effects, Nitsch *et al.* do concede that it may be detectable in exceptional circumstances where samples from bone with rapid turnover were taken from individuals who died shortly after pregnancy (Nitsch *et al.* 2010, p. 3197). PSN 911 was a 25-35yr female found buried at Cherry Hinton with a 36-40 week foetus in her abdomen, strongly suggesting she died pregnant. She provides the best case for testing whether pregnancy

can be detected in the Cambridgeshire isotope values. Her dentine collagen $\delta^{13}C$ values are low for the Cambridge population but her $\delta^{15}N$ values are high for Cherry Hinton and about average for the Cambridge population, however, her rib collagen $\delta^{13}C$ and $\delta^{15}N$ values are very low compared to all Cambridge groups, displaying a large decrease from her dentine collagen values. It is possible that as the pregnancy was nearly full-term, this may have been long enough to influence her rib collagen isotope values, causing a decrease in $\delta^{15}N$ values, as seen in Fuller *et al.* 2005. However, the decrease is 1.3‰, above the estimated decrease of 0.5-1.0‰ modelled by Nitsch *et al.* (2010, p. 3198). PSN 911 also has signs of childhood nutritional deficiencies as well as active endocranial and sinus inflammation at death, and may also have also undertaken short-distance migration between her childhood and adulthood (see Robb n.d. for an osteobiography). Unfortunately, therefore, despite a rare example of multi-isotope analysis of a woman who was likely to have died during pregnancy, it is still not possible to disentangle the possible effects of pregnancy from the possible effects of ill-health, changes in circumstances and diet from childhood to adulthood and migration from somewhere which may have had a different dietary signature.

9.2.2 Social Differences in Diet

The isotope values show potential differences in diet between the various groupings, although, as shown in Section 7.6, the inter-site differences were generally much greater than the intra-site differences. Site subgroup seems to be the greatest differentiating factor. This is largely to be expected as each High/Late Medieval site was chosen to represent a certain type of burial population i.e. town parish, friary, hospital. Each cemetery is likely to contain certain types of people (Section 4.4.2) - some sites would have had population overlap, e.g. people living in the parish of All Saints by the Castle could have been buried in the Hospital of St John under the right circumstances, but others did not, e.g. Augustinian Friars would not have been buried in the parish or Hospital cemeteries (Cessford in Robb n.d.). The Hospital cemetery would also have served a much wider catchment area than the parish cemetery of All Saints, taking inmates from across Cambridge (Cessford 2012). There is potential for high-status benefactors to have been buried at any of the sites, but this may have been more likely at some places than others (Cessford in Robb n.d.). While there are two 'rural' parish groups – Church End, Cherry Hinton

and Clopton - they are geographically distinct, which may also be expected to introduce some variation.

All Saints by the Castle and Church End, Cherry Hinton provide a reasonable semi-urban to rural comparison as the dating of the sites overlap, with both having burials dating from the High Medieval period. There is a difference in the isotope values at the two sites, with the evidence indicating that individuals from All Saints were more likely to have regular access to animal and/or aquatic proteins than Cherry Hinton. The differences in isotope values between the two sites are much more pronounced in the rib collagen, indicating these differences manifested in adulthood. When the dentine and rib isotopes are compared, they show that there is actually very little detectable increase in animal protein consumption between childhood and adulthood at Cherry Hinton whereas a general increase is seen at All Saints. This adds further evidence to the discussion in the previous section that at least at some sites there is evidence of differences between childhood and adult diet. Perhaps childhood diet was similar in both rural and urban groups, but then in adulthood, there was more choice and more social stratification for those living in the parish of All Saints than in Cherry Hinton, certainly, Cherry Hinton has far more individuals with low rib $\delta^{15}N$ values, indicating limited access to animal proteins, whereas All Saints has a few individuals with much higher rib $\delta^{15}N$ values than anyone at Cherry Hinton, indicating regular access. These findings broadly support evidence from historical sources that suggests that urban and rural diet would have differed, with rural populations generally eating less meat and marine fish, at least in the High Medieval period (Woolgar *et al.* 2006). There is however, an assumption that rural communities would have eaten a quantity of secondary animal products (milk, cheese, eggs, etc.) to meet their protein needs (Woolgar 2006a). The isotope evidence here suggests that whilst those at Cherry Hinton may have consumed these products, it was not in great enough quantities to greatly enrich their ^{15}N. Individuals at Cherry Hinton also have the lowest carbon isotope values of any group from High/Late Medieval Cambridgeshire. This is difficult to explain, particularly as the values appear to get more negative from childhood to adulthood, but is a phenomenon also seen at Wharram Percy (Richards *et al.* 2002, Britton *et al.* 2015), the archetypical Medieval poor rural site for isotope studies. Individuals at Wharram Percy have low $\Delta^{13}C$ values, although they also have much lower $\Delta^{15}N$ than Cherry Hinton (Figure 126), indicating that Cherry Hinton individuals were consuming more animal proteins than some other rural sites.

It is very clear from the isotope data that the Friary and the Hospital – the most explicitly religious organisations – are distinct in their isotope values, but in different ways. Individuals from the Friary generally have higher $\delta^{13}C$ and $\delta^{15}N$ values than most of the rest of the High/Late Medieval Cambridge population. Monastic orders following the rule of St Benedict should technically have been following a regulated, largely vegetarian diet with the addition of fish, although it is not clear how strictly each Order adhered to this (Woolgar 2006b, 2016, pp. 148–171). Less is known about what specific dietary regime the Augustinian Friars followed, and whether Friars may have experienced more variety as they tended to move between institutions, rather than largely being confined to one institution as Monks were. Clearly, at the Augustinian Friary in Cambridge, as the $\delta^{13}C$ and $\delta^{15}N$ values are both increased, there must be a considerable marine component to the diet, however, it is not possible to ascertain whether this was instead of, or in combination with meats and secondary animal products. Comparatively little animal bone was recovered from contexts associated with the Friary and those that could be identified were almost entirely domestic species (e.g. cow, sheep/goat, pig, domestic goose and Galliformes), as well as some cod, pike and ling (Rajkovača 2017, 2020, Hamilton-Dyer unpub.). The zooarchaeology suggests that the meat was not reared or processed in the Friary and that much of the food waste must have been deposited elsewhere (Rajkovača 2017, 2020), which unfortunately, does not help in quantifying the amount of meat in the diet compared to the rest of the population. However, the evidence for animal bone, particularly meat joints, does indicate that meat was consumed at least occasionally, and when it was, the zooarchaeology indicates there was a preference for mutton and chicken (Rajkovača 2017, 2020). Combining the isotopic, zooarchaeological and historical evidence gives a much more rounded picture of the diet in the Friary, with the isotope data providing evidence for fish consumption which is largely absent from the bone assemblage. There is also evidence of dietary hierarchy within the Friary, with those identified as 'Friary males' (but not Friars), having, on average, higher childhood $\delta^{13}C$ and $\delta^{15}N$ values than the 'Friars' (as identified by their clothed burials) but similar adulthood $\delta^{13}C$ and $\delta^{15}N$ values. This could indicate that those who chose to be buried in the Friary but were not explicitly part of the Order, were likely to be high-status individuals who had wealthy origins and could afford a diet rich in animal proteins throughout their life, and afford burial in an elite establishment. Evidence for burial requests in the Friary survive for a few individuals. These were from clerks, a burgess and a fellow of

King's College and all left numerous bequests, indicating some degree of wealth (Holder in Robb n.d.).

Novices in the Augustinian Order would have been admitted from the age of 14, although this dropped to c.10 after the Black Death (Roth 1966, pp. 136–7). Therefore, the dentine and rib isotope values should reflect pre- and post-induction in many individuals. The wide range in childhood $\delta^{13}C$ and $\delta^{15}N$ values in the Friars shows that they may have recruited from a cross-section of society. The comparisons of the childhood and adulthood diet in the Friary show an overall large increase and small range in $\delta^{13}C$ and $\delta^{15}N$ values in adulthood, further highlighting a wide pool of recruits and the effect of an institutionalised diet. A similar isotopic increase was also found in the individuals buried at Friaries in Northallerton and Newcastle-Upon Tyne (Kancle *et al.* 2018).

The Hospital of St John was also an inherently religious institution, albeit one that may have altered diet in relation to medical needs over religious ones, for example, by allowing meat for the sick on fasting days (Rubin 1987, p. 160). Unlike at the Friary, there is much less contextual information to distinguish who the burials are. The higher status members of the Hospital, such as the Masters and brethren, as well as major benefactors of the Hospital may have been buried in or around the Hospital Chapel (which was not part of the population sampled) (Cessford in Robb n.d., Cessford 2015). Therefore those buried in the detached cemetery are most likely to be a combination of Hospital inmates, Hospital servants, modest benefactors and corrodians (Cessford in Robb n.d., Rubin 1987). This potentially disparate collection of people is reflected in the wide range of the isotope values at the Hospital. There is likely to have been some hierarchy in the Hospital diet. The Master, brethren and corrodians would have had different access to foodstuffs to the inmates (Rubin 1987, p. 160). Conversely, inmates may have been given more meat than others based on medical beliefs at the time, with the provision of meat for the sick being explicitly mentioned in the rules of the Hospital (Rubin 1987, p. 160). It is likely that inmates were from a variety of backgrounds but were probably relatively local to Cambridge, although the Hospital owned land and property, connecting it with many surrounding villages (Cessford in Robb n.d., Underwood 2008, Cessford 2015). The inmates comprised of the 'deserving poor' – the sick and the weak (with exceptions) (Rubin 1987, p. 157), and may have included people who had a relatively well-off life, but fell on hard times,

which would further add to the wide range of isotope values. Another confounding factor is that we do not know how long inmates spent in the Hospital – some people may have had relatively acute illnesses and died quickly, while others may have had chronic illnesses, or were simply old and frail and may have spent many months or years in the Hospital (Rubin 1987). As bone collagen reflects an average of many years of diet (Hedges *et al.* 2007, Matsubayashi and Tayasu 2019), it would take several years in the Hospital for a person's isotope values to reflect the diet of the Hospital. Therefore, from the isotope data, we cannot pinpoint an institutional dietary signature, as we might be able to at the Friary, but the general characteristic of the population buried in the Hospital is very varied. Certainly, some people buried were consuming a diet as high in animal and marine proteins as those in the Friary and these are most likely to be corrodians. Comparing the Hospital of St John to isotope values from the Hospital of St Mary Spital London (Lakin 2009), and the Hospital of St Giles by Brompton Bridge (Müldner and Richards 2005, Bownes *et al.* 2018) it is clear that the isotope data varies between the three Hospitals, with both St Mary and St Giles having much higher human-faunal offset $\Delta^{15}N$ values than the Hospital of St John (Figure 128, Appendix V). A significant number of individuals at St Mary and St Giles (Müldner and Richards 2005, Bownes *et al.* 2018) had $\Delta^{15}N$ values above the typical human-faunal offset range of 3-6‰ (Hedges and Reynard 2007, O'Connell *et al.* 2012), indicating they were eating more omnivorous meat and/or aquatic proteins than at the Hospital of St John. St Giles also has a much smaller isotope range. Overall, this indicates that diet in Hospitals was not uniform and that a large range in values is not necessarily a characteristic trait of all Hospital cemeteries.

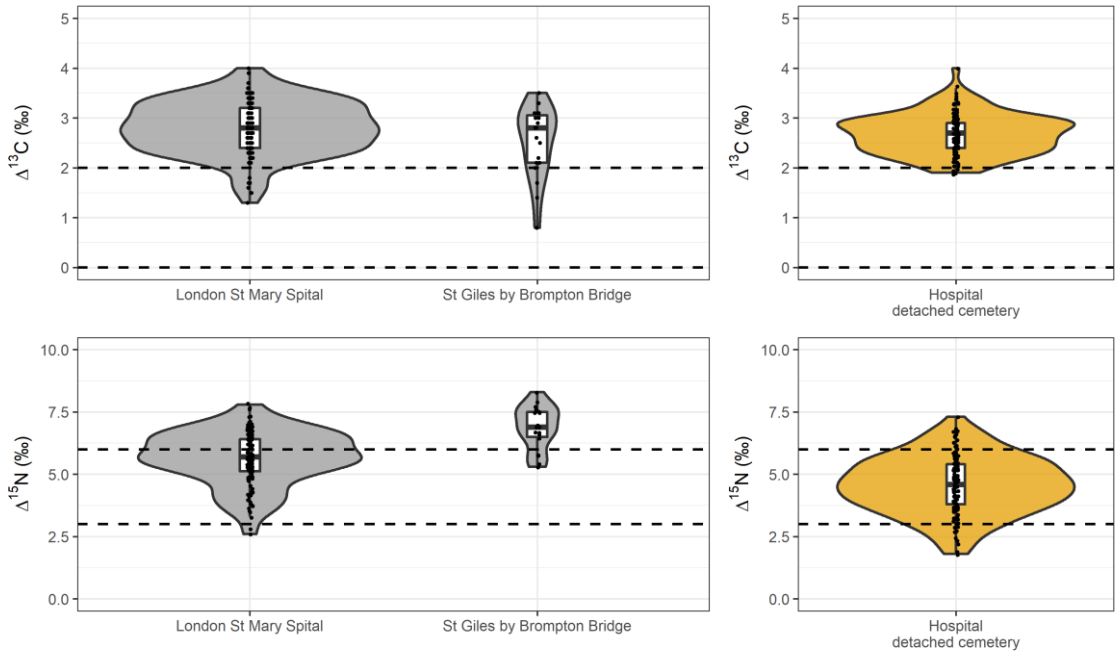


Figure 128: Violinplots showing human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N values for adults from the Hospitals of St Mary Spital, London (Lakin 2009), St Giles by Brompton Bridge, Yorkshire (Müldner and Richards 2005, Bownes et al. 2018) and the Hospital of St John, Cambridge.
Offset values are not absolute. Dashed black lines indicate typical human-faunal offset ⊿^{13}C range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

9.2.3 Longue Durée Diet

The most important finding from the longue durée approach is that the changes in diet, particularly in animal protein consumption, that occurred between the Early Medieval (Anglo-Saxon) and the High/Late Medieval periods eclipse any detectable changes *within* the High/Late Medieval period. It is likely that the changes observed can at least in part be attributed to the fish event horizon, estimated to have occurred around AD 1000 (Barrett *et al.* 2004), although the difference in site types and the way the sites have been divided by time period (splitting the Late Anglo Saxon and High Medieval at AD 1066), may somewhat mask the timing of this transition. However, there is not a large increase in $\Delta^{13}C$ to accompany the increase in $\Delta^{15}N$ values between the Late Anglo-Saxon and High Medieval period, which suggests that the changes in diet in this period were not all based on increased marine consumption. This could be evidence of increased freshwater fish consumption, as freshwater fish have relatively high $\delta^{15}N$ values combined with relatively low $\delta^{13}C$ values (Minagawa and Wada 1984, France and Peters 1997, Fuller *et al.* 2012). Freshwater fish could have been sourced from rivers or fishponds (Serjeantson and Woolgar 2006) but were also readily available in the fens to the North of Cambridge (Lucas *et al.* 1998, Sayer 2009, Cessford and Dickens 2019, pp. 197–198). The increase in $\Delta^{15}N$ values could also be a reflection of changing tastes and generally increased animal protein consumption, perhaps in part a result of the Norman conquest and increased urbanisation (Serjeantson 2006, Woolgar 2006a, Jervis *et al.* 2017, Craig-Atkins *et al.* 2020). When compared to offset longue durée data calculated from York (Müldner and Richards 2007b), similar broad temporal patterns are observed (Figure 129, Appendix V). At York, many of the High Medieval individuals had very similar isotope values to the Mid-Anglian population but *some* High Medieval individuals showed a considerable increase in carbon and nitrogen isotope values over the previous periods. In this case, it was interpreted that the fish event horizon was an influencing factor, but that in the initial stages, only certain individuals were consuming regular marine proteins and that the full effect of the fish event horizon took decades, if not centuries to show a detectable effect on the Medieval population (Müldner and Richards 2007b). Taking this interpretation into consideration, it is clear from the Cambridgeshire data that a similar pattern is present, with marine consumption increasing in the Late Medieval period. Of course, it should also be considered that the sites representing these periods are not good comparisons- the Late Anglo-Saxon period is represented by Gamlingay

only, which may not represent a typical population for the period. In addition, the faunal material chosen as an offset for the Gamlingay human isotope data was from a different site, and so the calculations of offset values may not be fully representative.

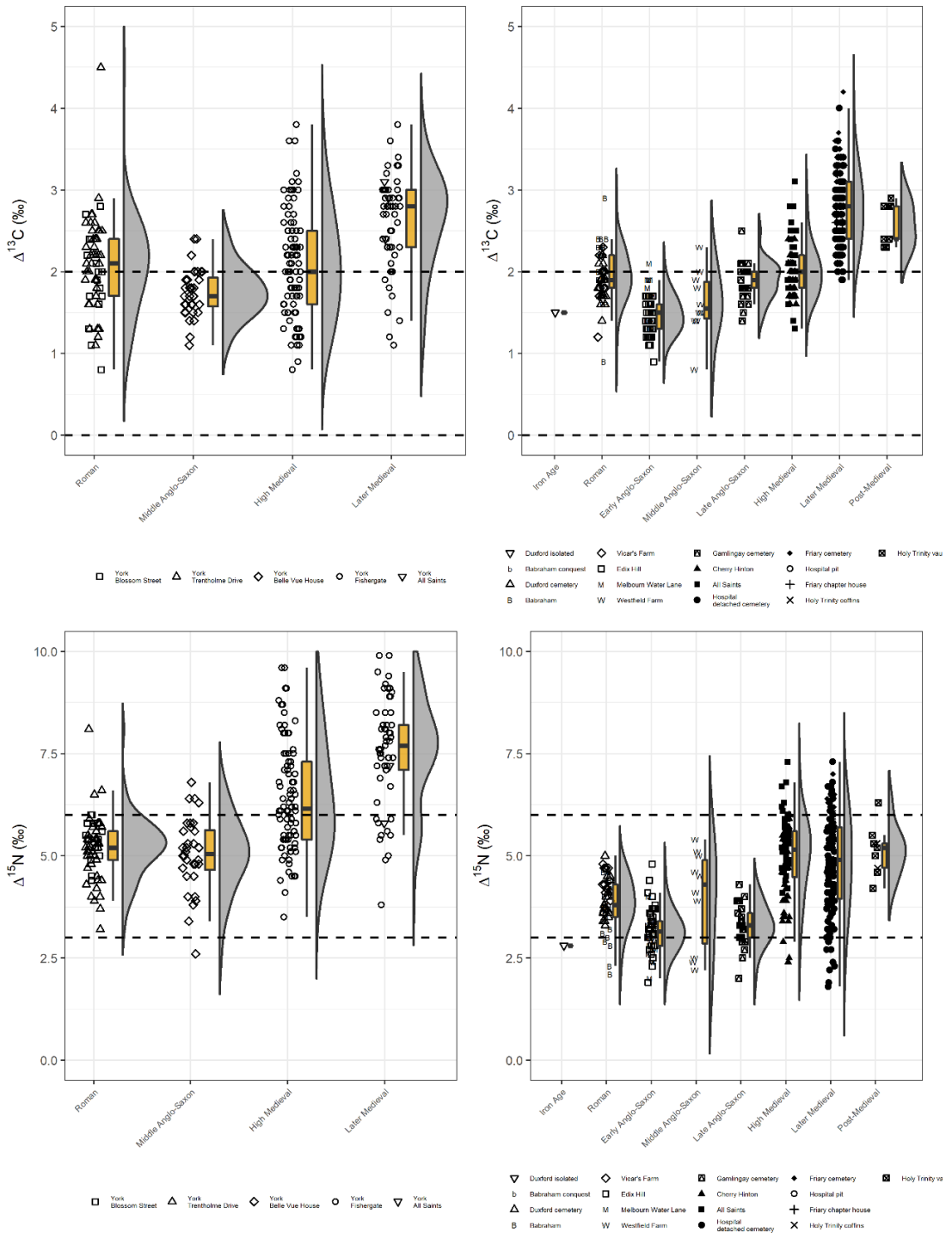


Figure 129: Raincloud plots showing human-faunal offset rib collagen ⊿^{13}C and ⊿^{15}N values for all adult Cambridgeshire and comparative individuals from York (Müldner and Richards 2007b) who were assigned to a British archaeological/cultural period. Offset values are not absolute. Dashed black lines indicate typical equivalent to one full trophic level effect ⊿^{13}C offset range of 0-2‰ (Bocherens and Drucker 2003) and typical human-faunal offset ⊿^{15}N range of 3-6‰ (Hedges and Reynard 2007, O'Connell et al. 2012)

9.3 Mobility and Migration in Medieval Cambridge

9.3.1 Characterising the 'Local' Isotope Signature

Chapter 2 set out some predictions for the expected 'local' isotope signature for Cambridge and the surrounding region based on the local geology and the BGS Biosphere Map (Lee *et al.* 2015, Evans, Chenery, *et al.* 2018, Evans, Mee, *et al.* 2018, British Geological Survey 2021). As can be seen in Table 67, the median $^{87}Sr/^{86}Sr$ values for all data from all High/Late Medieval sites is 0.7100. This is within the predicted range, although towards the higher end of the estimate. While using archaeological material to demonstrate bioavailable $^{87}Sr/^{86}Sr$ can be a partly circular exercise, as it can never be truly known if someone was 'local', the values generated in this thesis (excluding the outliers) are very homogeneous and seem to reflect the local geology. This data has enhanced the understanding of the local bioavailable $^{87}Sr/^{86}Sr$ and could be useful for future iterations of bioavailable $^{87}Sr/^{86}Sr$ maps for the Cambridgeshire region, particularly as this is an area that has been severely underrepresented in previous maps (Evans *et al.* 2012). The data demonstrates a novel approach to $^{87}Sr/^{86}Sr$ analysis, giving a truer representation of how many outliers may be expected in a systematically sampled population and will be useful for comparative archaeological studies in the future.

	BGS Predicted $^{87}Sr/^{86}Sr$				***$^{87}Sr/^{86}Sr$ Recorded***			
	Median	*Min*	*Max*	*Range*	*Median*	*Min*	*Max*	*Range*
Central Cambridge	0.7080-0.7090	0.7080	0.7101	0.0021	0.7100	0.7082	0.7134	0.0052
Cherry Hinton	0.7080-0.7090	0.7079	0.7086	0.0007	0.7100	0.7081	0.7108	0.0027
Clopton	0.7080-0.7090	0.7080	0.7101	0.0021	0.7100	0.7084	0.7110	0.0026
	BGS Predicted $\delta^{18}O_{carb}$ (VPDB)				***$\delta^{18}O_{carb}$ (VPDB) Recorded***			
	Median	*Min*	*Max*	*Range*	*Median*	*Min*	*Max*	*Range*
Central Cambridge	-	-5.3	-4.1	1.2	-4.9	-8.0	-2.4	5.6
Cherry Hinton					-5.1	-6.5	-3.7	2.8
Clopton					-4.8	-6.0	-3.8	2.2
	BGS Predicted $\delta^{18}O_{PO4}$ (VSMOW)				***$\delta^{18}O_{PO4}$ (VSMOW) Recorded (converted)***			
	Median	*Min*	*Max*	*Range*	*Median*	*Min*	*Max*	*Range*
Central Cambridge	-	16.6	17.7	1.1	17.0	13.7	19.6	5.9
Cherry Hinton					16.8	15.3	18.3	3.0
Clopton					17.1	15.8	18.2	2.4

Table 67: Predicted isotope values from the BGS Biosphere Map (Evans, Mee, *et al.* 2018) *for each geographical area with actual values recorded (outliers not excluded)*

The $\delta^{18}O$ values at all sites are much more varied and have a much greater range than the predicted values, despite their constricted geographical area. While the median enamel carbonate $\delta^{18}O$ values for the High/Late Medieval sites are within the estimated range, the minimum and maximum values are well above and below the estimates. In the case of the Cambridge town sites, there are several individuals who are >1.0‰ more negative than the estimate, but only one is flagged as an outlier. As discussed in Chapter 7, the range seen in Cambridge is well above ranges of expected normal variation (Lightfoot and O'Connell 2016), although the large range is not unprecedented in the region (Lucy *et al.* 2009). As this wide range in values is found throughout the Cambridgeshire data and there was good reproducibility for standards, this is very unlikely to be due to analytical error. This could lead to several interpretations: firstly, the cemetery populations could genuinely contain high numbers of people who spent their childhoods elsewhere. However, 96 of 195 (49%) High/Late Medieval values would fall outside the BGS range for Eastern Britain and 69 (35%) would fall outside the BGS range for Britain altogether (Evans *et al.* 2012, Evans, Chenery, *et al.* 2018). While not impossible, this would be an extremely high percentage of people who spent their childhoods a considerable distance from Cambridge. Such a high percentage of 'non-locals' has not been reported in other isotope studies of High/Late Medieval Britain (Jobling and Millard 2020).

Another explanation could be that the Cambridge area has considerably more natural variation in $\delta^{18}O$ values than previously seen in studies utilising $\delta^{18}O$ analysis, therefore exceeding predictions based on archaeological material. Identifying potential drivers for this is beyond the scope of this thesis but the flat topography, low altitude and relatively low rainfall in Cambridgeshire (Darling and Talbot 2003), or the complex hydrology of fenlands (e.g. Levy *et al.* 2014) could be factors relatively unique to the area which may have had an impact on the water cycle and consequent oxygen isotope ratios (Pederzani and Britton 2019).

Another explanation for variation could be the utilisation of water from a range of sources, such as rivers, springs or wells (Pederzani and Britton 2019, p. 80). Residents in Medieval Cambridge could obtain drinking water from a number of sites - archaeological evidence suggests that most people in High/Late Medieval Cambridge accessed their water from numerous urban wells of varying depth and quality (e.g. at the Augustinian Friary (Cessford 2017)). The Franciscan Friars in Cambridge constructed an aqueduct in 1325-7, bringing in

water from a source over 2.5km away (Willis and Clark 1886, pp. 427–30, 678–80), and there were also numerous brooks and springs, as well as the river. However, while the $\delta^{18}O$ values of water from rivers and lakes can deviate from local rainwater $\delta^{18}O$ values (Pederzani and Britton 2019, p. 80), this is usually due to influxes of water from a different source e.g. high altitude meltwater (Meier *et al.* 2013), or evaporation of large, open standing water sources (e.g. Gibson and Edwards 2002). These types of altitudinal and evaporation effects are not applicable to the water sources available in Cambridge, so while there may be some small variety in the $\delta^{18}O$ values between wells, springs and rivers due to variation in their replenishment and small scale evaporation (e.g. Hunt *et al.* 2005), it is probable that the values of all the sources generally reflected the local rainwater $\delta^{18}O$ values (Darling and Talbot 2003, Darling *et al.* 2003). Therefore it is unlikely that the variety of available water sources is accountable for the variation seen in the human $\delta^{18}O$ values.

Cultural modification to ingested water could also be a source of variation in $\delta^{18}O$ values. For most people in the High/Late Medieval period, including children, ale or beer was the predominant source of ingested water and an important part of the diet (Rawcliffe 2019, p. 254). Before the late 14th century, ale was brewed locally, often on a small scale (Bennett 1996). This means that local water supplies were probably used and due to the short shelf life of ale, it is likely that it was consumed very local to the source. After the Black Death, ale production expanded to meet increased demand (Bennett 1996), meaning some of the sources of water exploited for production were less localised. Beer, which has a much better shelf-life than ale, was also introduced in the late 14th century and by the 16th century, it predominated over ale (Pajic 2019). This means that from the 14th century, there is the potential that the main sources of ingested water in the diet were from a mix of ale and beer, some of which could have been produced relatively locally but some of which could have been produced further afield. Aside from the variation introduced by the source of water used for ale and beer, High/Late Medieval people would have participated in various processes that may have altered the ratio of oxygen isotopes, such as the physical act of brewing ale, making stews and pottage and cooking meats in different ways, e.g. roasting or boiling (Brettell *et al.* 2012, Royer *et al.* 2017). Unfortunately, it is not possible to quantify this modification in a way that can be used to investigate its effects on the High/Late Medieval isotope values. What can be said is that many food habits were ubiquitous, particularly ale drinking (Woolgar 2016, pp. 43–60, Rawcliffe 2019, pp. 254–255), so

if modification had an effect, it was probably experienced to some degree by most individuals, rather than just one group. Brewing, stewing and boiling result in an enrichment in ^{18}O in the remaining product, due to the evaporation of the lighter isotopes, with experiments suggesting various combinations of beer, stew and boiled water could result in increases of +0.6‰ to +4.4‰ over 'plain' ingested water (Brettell *et al.* 2012). Theoretically, regular consumption of these products during tooth development would result in a positive shift in $\delta^{18}O$ value in the consumer, although interestingly, the IQR of the High/Late Medieval $\delta^{18}O$ values is lower, rather than higher than the expected range for the East of Britain, with no high-value outliers. This suggests that if cultural modification was having a large effect, then the population's 'true' $\delta^{18}O$ values would be even lower than this, resulting in more questions regarding their origins and/or the estimation of the 'local' values. On the other hand, it does lend weight to the low-end outlier being a true outlier. Only two previous studies have investigated $\delta^{18}O$ values in archaeological material in Cambridgeshire, at Babraham and Westfield Farm (Friedman 2007, Lucy *et al.* 2009). These had ranges of 2.8‰ and 4.6‰ respectively. These results are also high and so ideally more ecological and archaeological investigations of $\delta^{18}O$ values in East Anglia are needed to tease apart these suggestions.

Climate change can also affect $\delta^{18}O$ values (Pederzani and Britton 2019, pp. 83–86). The High Medieval period in England was characterised by relatively warm conditions spanning c.950-1250, sometimes termed the 'Medieval Warm Period' or 'Medieval Climate Anomaly', followed by a transitional period of climatic instability, before a cooler period spanning c.1400-1700, termed the 'Little Ice Age' (Dawson *et al.* 2007, Mann *et al.* 2009, Slavin 2016). Despite this, it has been hypothesised that temperature changes in the British Holocene were not large enough to affect $\delta^{18}O$ values, however, this 'could only be confirmed when isotope variations through time can be established from a restricted locality' (Evans *et al.* 2012). The dataset generated in this thesis might be suitable to test this, however, the longue durée data actually shows lower $\delta^{18}O$ values in the High Medieval period than the Late Medieval period, the opposite of what may be expected based on the climate. It appears that in Cambridge, climate change is not particularly visible, or at least its potential effects are still difficult to distinguish from other factors, such as site type.

Unlike carbon and nitrogen isotope data, where potentially useful direct comparisons can be made to see how diet compares at different High/Late Medieval sites, comparisons of direct values for oxygen and strontium isotope analysis between Cambridgeshire sites and other sites are less useful. This is due to the geographically specific nature of the isotopes and the types of questions the data is being interrogated for. However, it may be useful to briefly compare results from this thesis with published values to see how the range in data and number of outliers differ. There is little comparable enamel carbonate data but in total, enamel phosphate $\delta^{18}O$ (SMOW) data is available for eight High/Late Medieval sites and enamel $^{87}Sr/^{86}Sr$ values are available from 12 High/Late Medieval sites in Britain as comparisons (see Appendix V for a gazetteer of sites and summary of the comparative data). A recent study has synthesised all isotope evidence for migration in Medieval England to date (Jobling and Millard 2020) (Figure 130). Overall, the comparative enamel phosphate $\delta^{18}O$ values show smaller ranges than seen at sites in Cambridgeshire. Only the Magistrates Court site in Hull has contemporary $\delta^{18}O$ data with a range above 3.0% although this site almost certainly had 'non-locals' (Roberts *et al.* 2013). As is to be expected on sites with different geologies most comparative sites have higher $^{87}Sr/^{86}Sr$ values than Cambridgeshire. Sites with mean and median values within the 0.7080-0.7100 range, e.g. Greater London (Lakin 2009), still display greater ranges than Cambridgeshire, which may be explained by targeted sampling strategies.

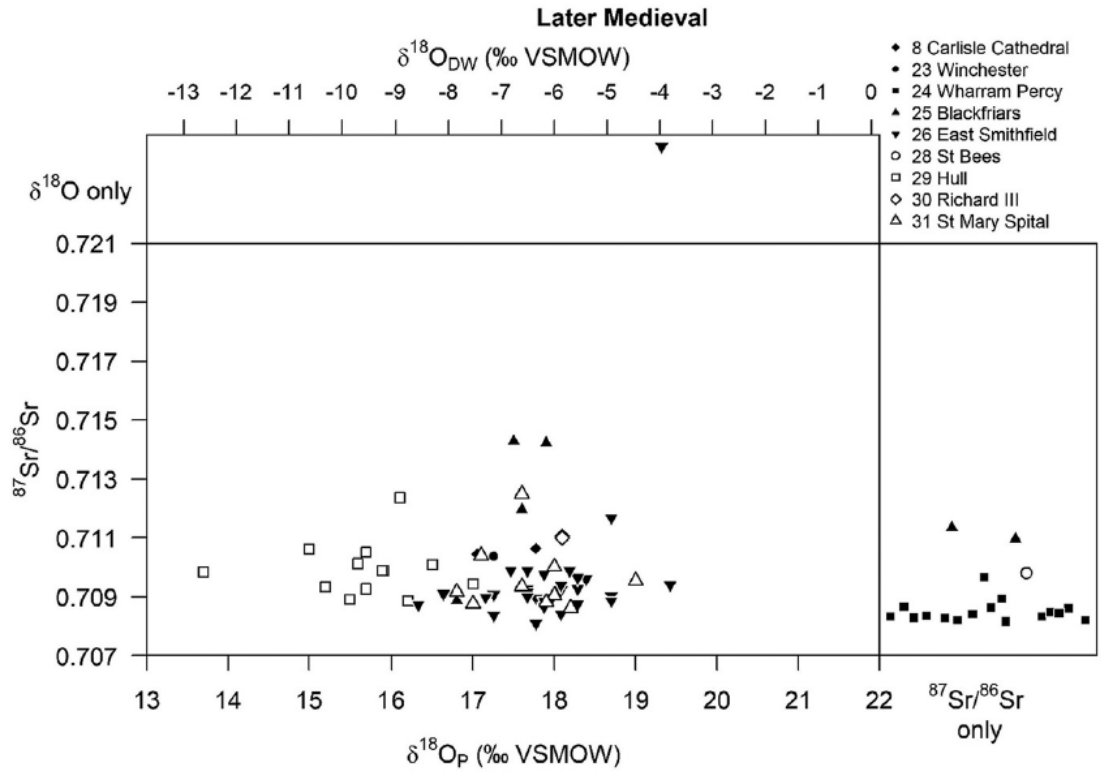


Figure 130: Comparative enamel phosphate $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values from High/Late Medieval sites in England (c.1100-1540), from Jobling and Millard (2020, p. 36)

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9.3.2 Detecting Migration in Cambridge

As discussed in Chapter 3, Cambridge is located in an area of geology with generic and undiagnostic $^{87}Sr/^{86}Sr$ values (Evans *et al.* 2012, Evans, Chenery, *et al.* 2018, Hoogewerff *et al.* 2019). The historical evidence in Chapter 2 indicates that many migrations, particularly from rural to urban centres, were likely to have been within 15km (e.g. Dyer 2020, p. 263), suggesting that shorter-distance migrants to Cambridge hailed from local Cambridgeshire villages, or from Norfolk and Suffolk (Cessford in Robb n.d.). Unfortunately, due to the homogeneity of the bioavailable $^{87}Sr/^{86}Sr$, this localised migration is largely invisible to the techniques employed in this thesis and so social and temporal changes cannot be quantified, but the historical and archaeological evidence attests that it certainly occurred.

Despite this, $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values from All Saints by the Castle may reveal short-distance migration of females. If the one outlier is excluded, the male $^{87}Sr/^{86}Sr$ values are extremely tightly clustered, ranging from 0.7085 to 0.7087 (n=5). If the outlying females are excluded, the remaining $^{87}Sr/^{86}Sr$ values have a much greater range from 0.7085 to 0.7100 (n=12) (Figure 78 in Section 7.5.2). Unfortunately, All Saints had a very low number of individuals who successfully produced $^{87}Sr/^{86}Sr$ *and* $\delta^{18}O$ results, but the pattern in the individual values is compelling. The population buried at All Saints by the Castle was likely to be a mixed cross-section of society, typical of a Medieval Parish population (Cessford in Robb n.d., see Section 4.5.2.2). Due to its location on the outskirts of Cambridge, it had both rural and urban associations and was connected to the surrounding agricultural land (Cessford in Robb n.d.). Surname evidence suggests that several families recorded in the Parish were not from Cambridge, with connections to local towns and villages but also other areas in Britain (Cessford in Robb n.d.). Due to these reasons, it is very plausible that migrants would be buried in All Saints and that a higher proportion of these might be shorter-distance migrant women due to rural-urban migration for marriage and/or employment, as discussed in Section 2.4.2. All Saints by the Castle was chosen to represent a 'typical' town parish and as such it effectively reflects the majority of the 'typical' lives of people living in High/Late Medieval Cambridge. Therefore, if the evidence from All Saints was effectively weighted to reflect its purpose as a proxy for 'typical' people, which would have made up the majority of the population of the

town, then the evidence suggests that greater migration of women may have been quite prevalent in High/Late Medieval Cambridge.

Unfortunately, some longer-distance migrant groups are also likely to be invisible in the isotope data. For example, the Netherlands are relatively close to East Anglia, had well-established trade networks with the East of England and in many ways, due to ease of water transportation over land transportation, Cambridge may have felt a closer connection to coastal countries across the English Channel, such as the Netherlands, than to the North and West of Britain (Ormrod *et al.* 2019, pp. 102–110). The alien subsidies indicate that the largest proportion of aliens recorded in Cambridge were 'Dutch' and so there is proof that migrants from this area were present (Ormrod *et al.* 2019, p. 107, England's Immigrants 1330-1550, version 1.0 2020). However, a recently produced bioavailable $^{87}Sr/^{86}Sr$ map of the Netherlands has $^{87}Sr/^{86}Sr$ values ranging from 0.7074 to 0.7113, with a median of 0.7091 (Kootker *et al.* 2016, p. 5), demonstrating that the bioavailable range of $^{87}Sr/^{86}Sr$ values for the whole of the Netherlands is within the range of the values recorded in Cambridge, making it impossible to identify this important migrant group using the available isotope data. In fact, much of the proximal North-eastern coastal areas of Europe, where the records of alien subsidies suggest much of the rest of the migration to Cambridge may be from, have the potential to have similar isotope values to East Anglia, including Northern France and the Paris basin, Belgium and Northern Germany (Willmes *et al.* 2018, Hoogewerff *et al.* 2019). Again, this means the potential to identify migrants from these areas is limited.

Despite the homogeneity of much of the data, a minority of individuals were identified as having $^{87}Sr/^{86}Sr$ values which place them as convincing outliers in comparison to the overall High/Late Medieval population, as well as one convincing $\delta^{18}O$ outlier (Table 68). As discussed in Chapter 2, travel and migration was not a rare occurrence in the High/Late Medieval period and historical evidence suggests that migrants were coming in from Britain and the continent. Based on the alien subsidies, it is likely that those coming in from outside of Britain largely originated from Western Europe although travel from further afield is not impossible (England's Immigrants 1330-1550, version 1.0 2020). Comparing the $^{87}Sr/^{86}Sr$ values of the outliers to estimations of values for Britain from the BGS Biosphere Map (Evans, Chenery, *et al.* 2018) (see Figure 131 below, and Section 3.5), estimations of global values (e.g. Hoogewerff

et al. 2019) (see Section 3.5) and previously published values from archaeological material (e.g. Evans *et al.* 2012, Jobling and Millard 2020), these individuals can largely be grouped into three categories. The first is individuals whose $^{87}Sr/^{86}Sr$ values are different to those expected for their site but could reasonably match values for a nearby area (Figure 131), although objectively, someone is no more likely to come from a nearby area with a similar value, than an area with the same value elsewhere. An example is PSN 907, whose $^{87}Sr/^{86}Sr$ values is 0.7095, which falls outside of the predicted range for Cherry Hinton, but is a very common $^{87}Sr/^{86}Sr$ value across Britain and could be consistent with nearby areas in Cambridge and Cambridgeshire (Evans, Chenery, *et al.* 2018). The second is individuals whose $^{87}Sr/^{86}Sr$ values do not match bioavailable $^{87}Sr/^{86}Sr$ values from Cambridge or the surrounding area but could match other areas in Britain. In the case of several of the outliers with values around 0.7108, for example, the values do not match with those predicted from geology on the Eastern side of Britain but similar values could result from geology found in areas in Wales, Cornwall and the Midlands, with the addition of some areas of Scotland and Sussex (Figure 131) (Evans, Chenery, *et al.* 2018, British Geological Survey 2021), but could also match anywhere in the world with similar geology (Hoogewerff *et al.* 2019). Surname evidence suggests that individuals from many counties in England may have migrated to Cambridge, but these are dominated by relatively nearby counties such as Lincolnshire, Bedfordshire, Northamptonshire and Essex, as well as Yorkshire and Lancashire, with no mention of Cornwall (Cessford in Robb n.d.). The alien subsidies for Cambridge show the Irish are the second most populous alien group in the 1440s tax records. They also mention the Scottish and Welsh but they are a very small minority (England's Immigrants 1330-1550, version 1.0 2020). The third group are individuals whose $^{87}Sr/^{86}Sr$ values do not match the majority of bioavailable $^{87}Sr/^{86}Sr$ for Britain (Figure 131) and are likely to have migrated from elsewhere (although no outliers in Table 68 definitively fall outside the maximum recorded values for Britain, listed as 0.7140 for England and 0.7165 for Scotland in Evans *et al.* (2012). The strongest candidate for this category is PSN 66 from the Hospital of St John, whose high $^{87}Sr/^{86}Sr$ value of 0.7134 is indicative of a childhood spent in an environment with older, more radiogenic bedrock geology. In Britain, geology which could produce these values is extremely limited, and largely constrained to Precambrian rock formations in the Malvern Hills and the Highlands of Scotland (Evans, Chenery, *et al.* 2018, British Geological Survey 2021) (Figure 131). The only published High/Late Medieval individual from a British site with a value of

0.7134 (Sk158 from Auldhame, East Lothian) was interpreted as potentially spending their childhood in 'areas of the Southern Uplands or areas of Perthshire and Aberdeenshire to the north of Lothian' (Lamb *et al.* 2012, p. 771). However, given the distance of Cambridge from Scotland, the limited scope for these values to originate in Britain, and the larger areas of geology in Europe (and beyond) which could result in these values (e.g. Hoogewerff *et al.* 2019)., it is therefore potentially more likely PSN 66 spent his childhood outside of Britain. A young adult female buried in the Hospital detached cemetery (PSN 322) also has a high $^{87}Sr/^{86}Sr$ value (0.7122). This value is not consistent with geology in most of England, but could be associated with areas of Palaeozoic sandstone, mudstone and limestone, largely in Wales and Scotland (Evans, Chenery, *et al.* 2018, British Geological Survey 2021). Analysis of a Late Medieval individual from Poulton Chapel, Cheshire also produced a $^{87}Sr/^{86}Sr$ value of 0.7122 and was interpreted as being relatively 'local', potentially having travelled from nearby areas of appropriate geology in Wales (Burrell *et al.* 2019). It is therefore unlikely that PSN 332 spent her childhood in England, but, it has been speculated, based on her high, non-local isotope values and her unusual burial in the Hospital as a young woman with no obvious pathology that she may have been part of a trading group - she may have died suddenly in Cambridge while visiting for trade and the Hospital cemetery may have been the logical place of burial for a passing visitor with no parish association (Robb in Robb n.d.). Contextualising knowledge of Medieval trade routes with areas which have geologies known to be associated with higher $^{87}Sr/^{86}Sr$ values, it has been suggested that PSN 332 could have spent her childhood in Southern Norway, which had strong trade links with Britain (Robb n.d., Barrett *et al.* 2008, 2011, Keller 2010, Price and Naumann 2014, Price *et al.* 2014, Barrett pers comm).

Combining $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ data in archaeological studies is usually serves to further eliminate unlikely geographical areas of origin (Bentley 2006, Pederzani and Britton 2019). However, due to the much greater variability in the $\delta^{18}O$ values seen in the Cambridgeshire data than in previous studies and the complications this causes for comparisons with established data distributions (as discussed in Section 9.3.1), in this case, including $\delta^{18}O$ values complicates the interpretation of the $^{87}Sr/^{86}Sr$ outliers. Taking the $\delta^{18}O$ data at face value and comparing it to distributions estimated by the BGS map, for example, dramatically increases the areas in Britain which the outliers are unlikely to have spent their childhoods (Evans, Chenery, *et al.* 2018) (Figure 131) and therefore increases the number of people that may have spent their childhoods

elsewhere. For example, PSN 1238 from Clopton has a $^{87}Sr/^{86}Sr$ value of 0.7110, which is higher than the estimated bioavailable $^{87}Sr/^{86}Sr$ for the village but could reasonably match values from nearby villages, such as Potton (Evans, Chenery, *et al.* 2018) (Figure 131), suggesting local scale migration. However, their carbonate $\delta^{18}O$ value is -6.0‰, which would place them outside of Britain according to estimations from the BGS map (Evans, Chenery, *et al.* 2018). As discussed above, it is far more likely that there is much greater variability in the 'local' signature than previously estimated, and causes for the variability are unknown, so it is difficult to determine whether to include the $\delta^{18}O$ values in estimations of origins. For this reason, while the $\delta^{18}O$ values should be noted, interpretations of the outliers in Cambridge should be primarily based on $^{87}Sr/^{86}Sr$ values (Table 68).

From these values and known historical association, speculation can be made about the origins of the outliers buried in Cambridge, as shown in Table 68, but ultimately, the strength of $^{87}Sr/^{86}Sr$ values (and $\delta^{18}O$ values to an extent), is to highlight people who almost certainly didn't spend their childhoods in Cambridge, rather than pinpoint where those outliers did spend their childhoods, which can be a flawed approach, biased by the bioavailable data (Pollard 2011, Lightfoot and O'Connell 2016). While it is interesting to estimate the potential regions that the individuals may have come from, ultimately for this thesis, the aim was to quantify how many outliers were present, whether there were differences in outliers between sites and social groups and whether the numbers changed through time. This thesis has identified a small number of convincing outliers (c.5-7%). As only extreme outliers have been detected, this small number is to be expected and is just above the 3.5% of taxpayers estimated to be aliens by Ormrod *et al.* (2019, p. 62). This thesis has shown that these individuals do not appear to conform to a particular pattern by site or social group and has shown that there are no convincing temporal changes, perhaps contradicting some expectations from historical evidence, particularly regarding increased migration after the Black Death.

A potentially surprising finding is the relative homogeneity of $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values in the Friary group. As an international organisation which encouraged travel for education, employment and pilgrimage (Roth 1958, 1966, Fredeman 1979) (see Chapter 2), it might be expected that the Friars would be the group most likely to be of diverse origins. An excellent explanation for this, as has been argued by Cessford (in Robb n.d., pers comm), is that Friars

followed a 'boomerang' lifecourse- they may have travelled and migrated extensively during their lifetime, but ultimately they tended to retire (and die) in the locality where they originated from. This can be seen in the example of John Capgrave given in Chapter 2, who despite living in multiple places, ultimately started and ended his life in Lynn (Fredeman 1979), which would leave no trace of his time at the Augustinian Friary in Cambridge, or anywhere else, in his isotopic legacy. This theory works well for older individuals who were buried in the Friary but may not work so well for young Friars who could potentially have died early in their careers/education. This could indicate that any young Friar who died who was from the local area was buried at the Friary in Cambridge, but others were transported back to their Parish of origin for burial.

Site Subgroup	***PSN***	***Est. Death Date***	***Sex***	***Age (yr)***	***Carbonate $\delta^{18}O$ (VPDB)***	***Phosphate $\delta^{18}O$ (VSMOW)***	***$^{87}Sr/^{86}Sr$***	***Comments on Possible Childhood Origin***
Cherry Hinton	907	High Medieval c.940-1170	F	46-59	-3.9	18.1	0.7095	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, but value very common across Britain, could be consistent with relatively nearby areas.
	918	High Medieval c.940-1100	M	26-35	-4.5	17.5	0.7108*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, could be consistent with areas across Britain – possibly areas in Midlands, Cornwall, Wales, S. Scotland.
	930	High Medieval c.940-1170	F	36-45	-5.2	16.7	0.7108*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, could be consistent with areas across Britain – possibly areas in Midlands, Cornwall, Wales, S. Scotland.
All Saints	728	High Medieval c.1050-1365	F	26-35	-8.0*	13.7	0.7086	$^{87}Sr/^{86}Sr$ values consistent with Cambridge area but $\delta^{18}O$ values are very low and not consistent with British values, could be from an area with similar geology but colder climate e.g. Norway/Denmark?
	746	High Medieval c.1050-1250	M	36-45	-4.7	17.3	0.7113*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, could be consistent with areas across Britain – possibly Midlands, Sussex, Cornwall, Wales, Scotland.
	781	High Medieval c.940-1365	F	26-35	-5.9	15.9	0.7104	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, could be consistent with areas across Britain - possibly areas in Midlands, Cornwall, Sussex,

Site Subgroup	*PSN*	*Est. Death Date*	*Sex*	*Age (yr)*	*Carbonate $\delta^{18}O$ (VPDB)*	*Phosphate $\delta^{18}O$ (VSMOW)*	*$^{87}Sr/^{86}Sr$*	*Comments on Possible Childhood Origin*
								Wales and Scotland, but $\delta^{18}O$ values are very low and not consistent with British values. Difficult to place, possibly somewhere with colder climate?
Hospital detached cemetery	66	Late Medieval c.1270-1380	M	18-25	-4.7	17.2	0.7134*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, or much of England. Could possibly be consistent with areas in Wales or Scotland or outside Britain, such as Northern France/Portugal/Spain?
	99	Late Medieval c.1330-1400	M	26-35	-4.7	17.2	0.7115*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, or much of England. Could be consistent with areas in Wales or Scotland, or outside of Britain.
	332	Late Medieval c.1264-1308	F	18-25	-4.8	17.1	0.7122*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, or much of England. Could be consistent with areas in Wales or Scotland, or outside of Britain.
Clopton	1238	Late Medieval c.1200-1561	M	26-35	-6.0	15.8	0.7110*	$^{87}Sr/^{86}Sr$ values not consistent with Cambridge area, could be from Britain - possibly areas in Midlands, Sussex, Cornwall, Wales and Scotland, but $\delta^{18}O$ values are very low and not consistent with British values. Difficult to place, possibly somewhere with colder climate?

*Table 68: Individuals highlighted as outliers by boxplots and/or by DDC analysis (highlighted with *) for enamel carbonate $\delta^{18}O$ and enamel $^{87}Sr/^{86}Sr$ values, with comments on their possible childhood origins. Comments are based on comparisons with previously published studies and biosphere maps (Bowen and Revenaugh 2003, Darling et al. 2003, Evans et al. 2012, Bowen 2015, Evans, Chenery, et al. 2018, Hoogewerff et al. 2019)*

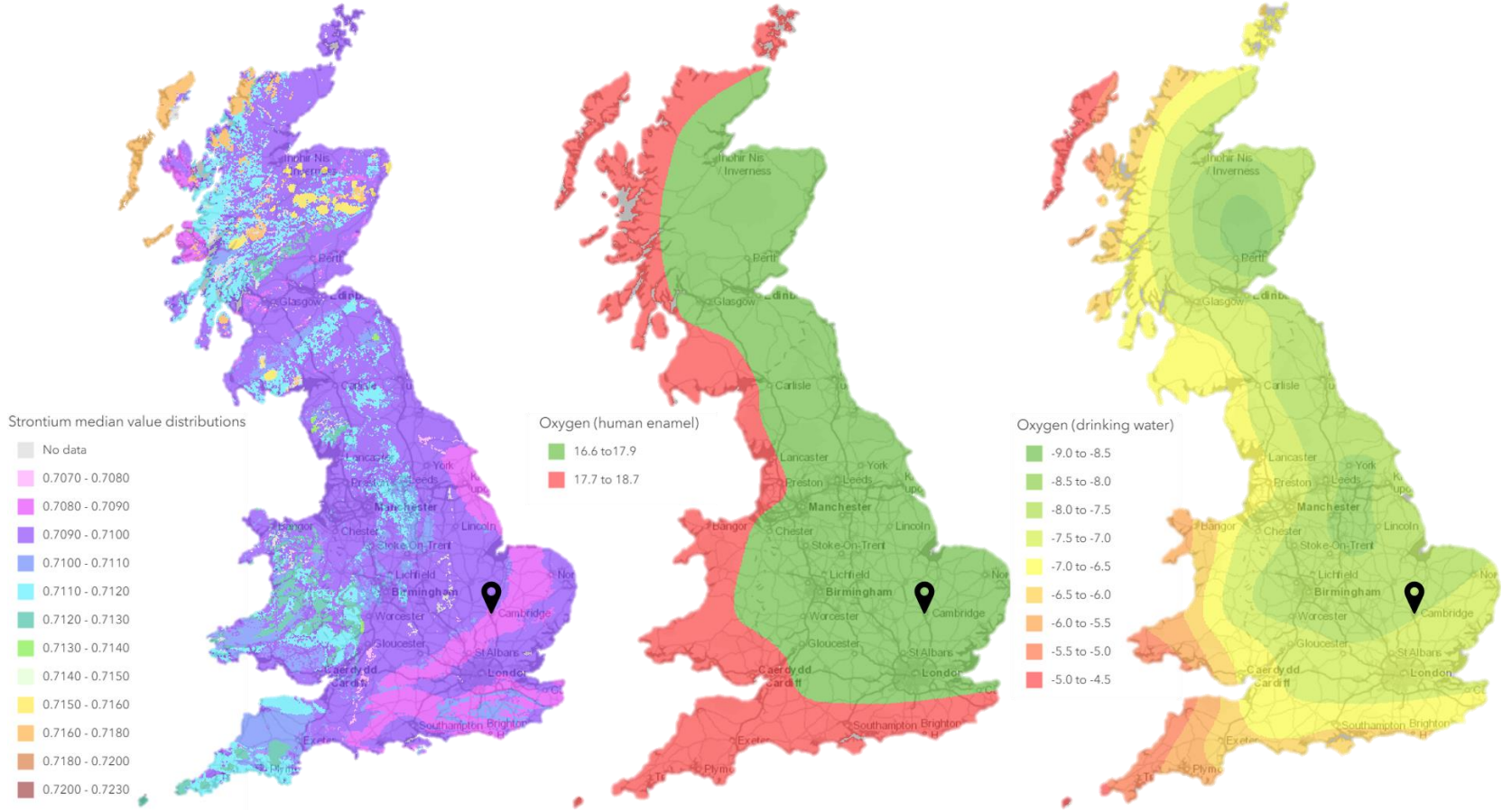


Figure 131: The British Geological Survey Biosphere Isotope Domain GB Online Map showing: (left) the layer for strontium median value distributions ($^{87}Sr/^{86}Sr$), (middle) the layer for $\delta^{18}O$ PO4 ‰ (VSMOW) (human tooth enamel) (after Evans et al. 2012), (right) $\delta^{18}O$ drinking water ‰ (VSMOW) (after Darling et al. 2003) (Evans, Mee, et al. 2018). Figure adapted from Evans, Chenery, et al. (2018), with location of Cambridge highlighted.

[Created using the Biosphere Isotope Domains GB (V1): Interactive Website, British Geological Survey © UKRI 2021. All rights reserved, contains OS Open Data]

9.4 High/Late Medieval Change and the 14th Century

Despite the knowledge that the High/Late Medieval period was one of social and economic changes, this thesis has shown that detecting associated temporal changes in the isotope data has been challenging and difficult to interpret. It is well known that the 14th century in particular was a period of great upheaval, with climate change, crop failures, famine, livestock murrains, widespread plague, population decline and social and economic change (Hatcher 1977, Mann *et al.* 2009, Campbell and Gráda 2011, Slavin 2012, 2014, 2016, Campbell 2016), yet for all intents and purposes, this is largely invisible in the isotope data. Historical documentary evidence for improved diet and increased meat consumption after the Black Death (e.g Woolgar 2006a) was expected to result in enriched ^{15}N in those living post-1350 and it was hoped that the documented social upheavals and increased migration after the Black Death (e.g. McClure 1979, 2020) would be seen in increased diversity in the oxygen and strontium isotope data. However, neither pattern is conclusively present.

The $^{87}Sr/^{86}Sr$ values at the Hospital detached cemetery alone hint at some pre/post-1350 changes in mobility, but only on a localised scale. A number of the pre-1350 Hospital individuals cluster tightly, with values similar to contemporary individuals from All Saints by the Castle and the Friary cemetery, indicating these may be people who spent their childhoods close by (seen in Figure 96). Post-1350, the values at the Hospital are more scattered and widespread, indicating increased population diversity, but all still within the estimated 'local' $^{87}Sr/^{86}Sr$ range. During the High/Late Medieval period in Cambridge attitudes towards charity changed (Rubin 1987, pp. 54–73) as did the types of people who sought charity (Rubin 1987, pp. 33–53). This was strongly related to economic fluctuations, which would in part have been driven by the events of the 14th century, including the Black Death (*ibid.*). This could explain the increased diversity and potentially increased catchment area of people seeking charity post-1350. However, the pattern in the $^{87}Sr/^{86}Sr$ values at the Hospital is less clear cut when assessed by Medieval century. It is likely that the potential changes in the population buried in the cemetery are linked to the progressive changes in the function and status of the Hospital. It was originally founded by the community to provide basic care to the poor and sick, but after it was granted

ecclesiastical status in the 13th century, it became increasingly liturgical, and in the 15th century it gained privileges afforded to University institutions, making it similar to the Colleges (Rubin 1987, pp. 111, 183). Therefore, changes in the population buried at the Hospital of St John were intrinsically linked to temporal changes in social and charitable attitudes in relation to economic fluctuations, but they cannot be linked to a singular event such as the Black Death.

Nevertheless, the lack of clear temporal change across the social groups in Cambridgeshire is an interesting observation, which highlights several dilemmas for isotopic and archaeological analyses. Firstly, perhaps the evidence suggests that events, particularly those in the 14th century, did not have as great an effect as assumed from historical evidence, at least not in Cambridge. Perhaps Cambridge was 'buffered', maybe by its relative wealth and unusual, relatively stable, social structure afforded by the university and numerous religious establishments? A second consideration is the choice of archaeological material – the temporal analysis certainly suffers from a lack of post-1350 data, and from a lack of sites which have well-dated individuals across multiple centuries. This unfortunately largely leads to a temporal comparison of apples and oranges, with the exception of the Hospital of St John. However, the changes discussed above, as well as the selective admission criteria and potential mix of inmates, staff and corrodians in the Hospital cemetery mean this cannot be a good representation of 'typical' people through time. Thirdly, the limitations of isotope analysis should be considered – perhaps many of the changes were too small, or subtle to be detected by isotope analysis. Conversely, possibly the events of the 14th century were just so numerous and had such repeated effect that there is no one dramatic period of change, but repeated, and ultimately for this type of data analysis, undetectable fluctuations? Certainly, the analysis of migration has been hampered by the masking of much short and long-distance migration by the homogenous local geology, but maybe changes in diet were also masked, such as cases where people sought out better quality cuts of meat, rather than overall increased meat consumption. Ultimately, it is likely to be a combination of all these factors – historical accounts and archaeological evidence from Cambridgeshire suggest that it was affected by the events of the 14th century – crops failed, the population fluctuated and skeletons show evidence of *Y.pestis*, confirming plague was present but ultimately, Cambridge was not deserted, and plague victims were largely given normative burials, suggesting that the town was not overwhelmed. Indeed, much new development was

carried out in the mid-14th century. Overall, Cambridge may not have been as badly affected as some areas.

9.5 Isotope-Driven Osteobiographies

As a final integration of isotope analysis with other evidence to reconstruct what life may have been like in Medieval Cambridge, this section will attempt several brief 'osteobiographies'. Osteobiographies differ from text-based historical biographies in the nature of the evidence drawn upon, principally information from skeletal material, and the observations that can be made from these sources. Osteobiographies 'afford history for those below the textual threshold' (Robb *et al.* 2019, p. 29) and are a powerful tool in reconstructing lifecourse for the majority of the High/Late Medieval population who were not documented (Gilchrist 2012, pp. 43–67). The multi-tissue, multi-isotope analysis employed in this thesis has generated a considerable amount of information for many individuals, which lends itself to individual lifecourse analysis.

Detailed osteobiographies of a number of individuals from Medieval Cambridge have been constructed as part of the 'After the Plague' project, using the large amount of osteological, palaeopathological, metrical, genetic and isotope data generated, coupled with archaeological and historical information (Robb n.d., Robb *et al.* 2019). However, those identified as part of the project as having the most suitable information to build a general osteobiography were not necessarily those with the most distinctive isotope information. Therefore, this section will take a similar multidisciplinary approach, using data produced by the 'After the Plague' project (Robb n.d.), in conjunction with isotopic data, to discuss individuals whose isotope values may reveal information about their lifecourse, particularly if their isotope values deviated from expected values according to DDC analysis (Section 7.9.3). There are several comparable examples of this approach for Medieval individuals in Britain, most prominent being the identification of lifestyle changes in King Richard III (Lamb *et al.* 2014) and the investigation of the identity of the 'St Bees Lady' (Knüsel *et al.* 2010).

9.5.1 PSN 203

PSN 203 [skeleton 1277, feature 716]		
Basic Information	Skeletal condition	75-100% complete, good preservation (Brickley and McKinley 2004, Mitchell and Brickley 2017)
	Sex	Male: overall os coxae features = male (Phenice 1969, Ferembach *et al.* 1980, Buikstra and Ubelaker 1994, Brickley 2004); overall skull features = male (Keen 1950, Ferembach *et al.* 1980, Buikstra and Ubelaker 1994, Schwartz 2007); aDNA = XY, male (Skoglund *et al.* 2013)
	aDNA (human)	mtDNA: H3K (Andrews *et al.* 1999, Kloss-Brandstätter *et al.* 2011), YChr: R1b-L754, predicted brown eyes, brown/dark brown hair, intermediate skin (Walsh *et al.* 2014, 2017, Chaitanya *et al.* 2018)
	Assigned social group	Hospital male
Childhood and growth	Approx. birth date	AD 1180-1380 (estimated from death date minus median age at death)
	Childhood pathology	Enamel hypoplasia present but only 1 tooth affected with 1 defect (Goodman and Rose 1990, Hillson 1996)
	Childhood diet (isotopes)	Dentine collagen $\delta^{13}C$ = -18.0‰, $\delta^{15}N$ = 15.3‰, enamel carbonate $\delta^{13}C$ = -12.1‰ *(Hospital male means: dentine collagen $\delta^{13}C$ = -19.1‰, $\delta^{15}N$ = 12.1‰, enamel carbonate $\delta^{13}C$ = -12.7‰)*
	Final stature	166.2cm, based on mean of R&L femur length of 44.1cm (Trotter and Gleser 1952) *(Hospital male mean = 169.5cm; min = 160.9cm; max =177.1cm)*
Adulthood	Indices	Brachial index = 71.2; crural index = 81.0 (Schwartz 2007)
	Entheses	Nothing unusual reported
	Osteoarthritis	R&L shoulder, R elbow, R&L wrist, R&L hip, L knee, spine (Brothwell 1981, Rogers and Waldron 1995)
	Trauma	None reported
	Other pathology	Cribra orbitalia (scarring, almost obliterated) (Stuart-Macadam 1982, 1991), maxillary sinusitis (disorganised woven bone/spicules) (Boocock *et al.* 1995), subchondral cyst in R acetabulum, periosteal new bone (Ortner 2003), 3 Schmorl's nodes (Rogers and Waldron 1995)
	aDNA (pathogen)	None reported
	Dentition	18 teeth present, 3 teeth lost ante-mortem, 3 teeth with caries, periodontal disease present = 4/severe (Ogden 2007), calculus present = 3/severe (Brothwell 1981)
	Adult diet (isotopes)	Rib collagen $\delta^{13}C$ = -18.3‰, $\delta^{15}N$ = 15.2‰ *(Hospital male means: rib collagen $\delta^{13}C$ = -18.9‰, $\delta^{15}N$ = 12.6‰)*
	Mobility (isotopes)	Enamel carbonate $\delta^{18}O$ = -4.4‰, enamel $^{87}Sr/^{86}Sr$ = 0.7087 *(Hospital male enamel carbonate $\delta^{18}O$ mean = -4.4‰, enamel $^{87}Sr/^{86}Sr$ median = 0.7091)*
Death and burial	Age at Death	Likely age range: 60+yr, median age 70yr, broadly 'old adult', based on pubic symphysis = 5 (Brooks and Suchey 1990), auricular surface = 5 (Buckberry and Chamberlain 2002), sternal rib ends = 7 (İşcan *et al.* 1984), full clavicular, spheno-occipital, sacral and hyoid fusion and full dental eruption (Scheuer and Black 2000).
	Estimated death date	AD 1250-1450, estimated median death date = 1350 (Cessford and Alexander in Robb n.d.). Cannot be certain if died pre- or post-1350
	Burial treatment	Normative burial in the detached cemetery of the Hospital of St John the Evangelist (Cessford 2015)

Table 69: Key data generated by the 'After the Plague' project pertaining to PSN 203 (includes references for methods and standards used for recording the data)

PSN 203 was a man who may have had brown eyes and brown hair although as he lived to 60+years, this had probably faded to grey in his later years. His dating is vague, but he is likely to have lived sometime in the 13th to 15th centuries, potentially living through some of the tumultuous 14th century. PSN 203 shows no sign of nutritional or environmental stress in his childhood and would have grown to just below average height for males in the Hospital. His dentine $\delta^{13}C$ and $\delta^{15}N$ values are unusual, with the second highest $\delta^{15}N$ value of any High/Late Medieval individual sampled. His rib $\delta^{13}C$ and $\delta^{15}N$ values are also similarly high, making him unusual in the fact that he shows very little change between his dentine and rib values, but also by having the highest rib $\delta^{15}N$ value out of any High/Late medieval individual sampled in Cambridge. In later life, he did suffer with severe arthritis and general joint degeneration throughout his body and had lost some teeth, with the remaining displaying caries, calculus and periodontal disease, although this is very normal for older individuals. PSN 203 was eventually buried in the Hospital detached cemetery. This could mean a few scenarios happened in his life. Firstly, he could have been part of the 'deserving poor' who fell ill with an ailment that qualified him to enter the Hospital, where he eventually died and was buried. Secondly, he could have worked at the Hospital and chose to be buried there. Thirdly, he could have been a corrodian who paid to reside and/or be buried in the Hospital. Given his unusual, and constant dietary isotope signature, this implies that he was unlikely to be poor and he was either unlikely to have spent enough time in the Hospital for his dietary isotopes to reflect the institutionalised diet in the hospital, or he was given a different diet to the rest of the inmates. Weighing up the evidence, it is most likely that this individual was a corrodian, who, if they did spend some time in the Hospital in their later years, paid to continue to eat a diet richer in animal proteins than much of the rest of the population of Cambridge had access to. As he could afford a corrody, and a diet potentially abundant in animal proteins, he could have been a relatively rich and influential person in High/Late Medieval Cambridge.

9.5.2 PSN 519

PSN 519 [skeleton 1602, feature 265]		
Basic Information	Skeletal condition	75-100% complete, good preservation (Brickley and McKinley 2004, Mitchell and Brickley 2017)
	Sex	Male: overall os coxae features = male (Phenice 1969; Buikstra *et al.* 1994; Brickley 2004; Ferembach *et al.* 1980); mandibular features = ?female; overall skull features = male (Keen 1950, Ferembach *et al.* 1980, Buikstra and Ubelaker 1994, Schwartz 2007); aDNA = XY, male (Skoglund *et al.* 2013)
	aDNA (human)	mtDNA: U5a1a1 (Andrews *et al.* 1999, Kloss-Brandstätter *et al.* 2011); no phenotype data
	Assigned social group	Friars
Childhood and growth	Approx. birth date	AD 1279.5-1308.5 (estimated from death date minus median age at death)
	Childhood pathology	None reported except for possible enamel hypoplasia present but recording unfinished (Goodman and Rose 1990, Hillson 1996)
	Childhood diet (isotopes)	Dentine collagen $\delta^{13}C$ = -19.1‰, $\delta^{15}N$ = 10.8‰, enamel carbonate $\delta^{13}C$ = -12.8‰ *(Friar means: dentine collagen $\delta^{13}C$ = -19.0‰, $\delta^{15}N$ = 12.3‰, enamel carbonate $\delta^{13}C$ = -12.9‰)*
	Final stature	164.0cm, based on L femur length of 43.1cm (Trotter and Gleser 1952) *(Friary male mean = 173.8cm, min = 164.0cm, max = 179.0cm)*
Adulthood	Indices	Brachial index: 78.0; crural index: 82.1 (Schwartz 2007)
	Entheses	Large enthesopathies on patellae and fibula. Quite pronounced soleus attachments. High enthesopathy scores.
	Osteoarthritis	Temporo-mandibular joint, R&L hip, feet, spine (Brothwell 1981, Rogers and Waldron 1995)
	Trauma	Possible avulsion fracture anterior talus facet on R calcaneus, not conclusive
	Other pathology	Large supra-acetabular cyst (penetrating through the outside of the ilium), osteochondritis dessicans, scarring on the visceral surfaces of ribs (Ortner 2003), 1 Schmorl's node (Rogers and Waldron 1995)
	aDNA (pathogen)	None reported
	Dentition	32 teeth present, 4 teeth with caries, periodontal disease present = 3/moderate (Ogden 2007), calculus present = 2/moderate (Brothwell 1981)
	Adult diet (isotopes)	Rib collagen $\delta^{13}C$ = -18.3‰, $\delta^{15}N$ = 14.2‰ *(Friar means: rib collagen $\delta^{13}C$ = -18.4‰, $\delta^{15}N$ = 13.9‰)*
	Mobility (isotopes)	Enamel carbonate $\delta^{18}O$ = -6.0‰, no enamel $^{87}Sr/^{86}Sr$ data *(Friar enamel carbonate $\delta^{18}O$ mean = -5.6‰)*
Death and burial	Age at Death	Likely age range: 36-45yr, median age 40.5yr, broadly 'middle adult', based on pubic symphysis = 4 (Brooks and Suchey 1990), auricular surface = 3 (Buckberry and Chamberlain 2002), sternal rib end = 5 (İşcan *et al.* 1984), full clavicular, spheno-occipital, sacral fusion and full dental eruption (Scheuer and Black 2000).
	Estimated death date	AD 1320-1349, estimated median death date = 1334.5 (Cessford and Alexander in Robb n.d.). Died pre-1350.
	Burial treatment	Buried with copper alloy buckle in cemetery of the Augustinian Friary (Cessford 2017).

Table 70: Key data generated by the 'After the Plague' project pertaining to PSN 519 (includes references for methods and standards used for recording the data)

PSN 519 was born sometime between AD 1279-1308. He was an Augustinian Friar and would have entered the order after the age of 14.. His dentine $\delta^{13}C$ and $\delta^{15}N$ values are well below the mean for the Friary, and quite low compared to the town population in general. At 164cm, he was also one of the shortest men in the Friary group and would have been short compared to the general parish population, which may be related to his potentially meagre diet. At some point, he is likely to have suffered a chest infection, leaving scarring on the inside of his ribs, although these healed during his life. He potentially suffered an avulsion fracture to his calcaneus in his right foot, which later healed but his feet also show signs of arthritis and possibly even gout. He has evidence of arthritis in both of his hips, which combined with the issues in his feet mean it may have been painful for him to walk in his later years. What is most interesting about PSN 519 is the change in his diet from childhood to adulthood – between the ages of c.7.5-12.5yr and his later adulthood, his $\delta^{13}C$ and $\delta^{15}N$ values dramatically increase, ending up just above the mean for the Friars and well above the mean values for the other High/Late Medieval Cambridge groups. This attests to switching from the general diet from his childhood household, to the institutionalised diet of the Augustinian Friars, which must have included much more animal and marine proteins than he had grown up with. This could be the story of a local boy from a relatively humble background entering a religious lifestyle and ending up in one of the most important Friaries of the Augustinian Order. He died aged 36-45yr sometime between 1320 and 1349 so he probably lived through events of the early 14th century, such as the famines and murrains (although these are not visible in his isotope ratios). There is a small chance that he could have died from the plague in 1349, although no evidence of *Y.pestis* was found. He was buried in the manner of a Friar - clothed in the attire of his Order, fastened with a copper alloy buckle.

9.5.3 PSN 746

PSN 746 [skeleton B26IV]		
Basic Information	Skeletal condition	75-100% complete, good preservation (Brickley and McKinley 2004, Mitchell and Brickley 2017)
	Sex	Male: overall os coxae features = male, sacral features = male; (Phenice 1969; Buikstra *et al.* 1994; Brickley 2004; Ferembach *et al.* 1980); mandibular features = male; overall skull features = ?male (Keen 1950, Ferembach *et al.* 1980, Buikstra and Ubelaker 1994, Schwartz 2007); aDNA = XY, male (Skoglund *et al.* 2013)
	aDNA (human)	mtDNA: H6a1a (Andrews *et al.* 1999, Kloss-Brandstätter *et al.* 2011), no phenotype data
	Assigned social group	Parish male
Childhood and growth	Approx. birth date	AD 1009.5-1209.5 (estimated from death date minus median age at death)
	Childhood pathology	None present
	Childhood diet (isotopes)	Dentine collagen $\delta^{13}C$ = -19.8‰, $\delta^{15}N$ = 11.3‰, enamel carbonate $\delta^{13}C$ = -14.5‰ *(Parish male means: dentine collagen $\delta^{13}C$ = -19.5‰, $\delta^{15}N$ = 11.9‰, enamel carbonate $\delta^{13}C$ = -13.0‰)*
	Final stature	184.6cm, based on average of L&R femur length = 57.6cm (Trotter and Gleser 1952) *(All Saints male mean = 171.1cm, min = 153.0cm, max = 184.6cm)*
Adulthood	Indices	Brachial index: 74.2; crural index: 82.2 (Schwartz 2007). Clavicle has an interesting morphology. Large and robust.
	Entheses	Nothing unusual reported
	Osteoarthritis	Spine (Rogers and Waldron 1995)
	Trauma	None reported
	Other pathology	Subchondral cyst in L acetabulum, healed periosteal new bone growth on tibiae and fibulae, bony extensions on MT1, hallux valgus (Ortner 2003), 6 Schmorl's nodes (Rogers and Waldron 1995)
	aDNA (pathogen)	None reported
	Dentition	23 teeth present, 1 tooth lost ante-mortem, 5 teeth with caries, periodontal disease present = 3/moderate (Ogden 2007), calculus present = 2/moderate (Brothwell 1981), periapical lesion present (Hillson 1996)
	Adult diet (isotopes)	No rib collagen $\delta^{13}C$ or $\delta^{15}N$ data *(Parish male means: rib collagen $\delta^{13}C$ = -19.3‰, $\delta^{15}N$ = 12.5‰)*
	Mobility (isotopes)	Enamel carbonate $\delta^{18}O$ = -4.7‰, enamel $^{87}Sr/^{86}Sr$ = 0.7113 *(Parish male enamel carbonate $\delta^{18}O$ mean = -5.3‰, enamel $^{87}Sr/^{86}Sr$ median = 0.7086)*
Death and burial	Age at Death	Likely age range: 36-45yr, median age 40.5yr, broadly 'middle adult', based on pubic symphysis = 4 (Brooks and Suchey 1990), auricular surface = 3 (Buckberry and Chamberlain 2002), sternal clavicle degeneration = 1 (Falys and Prangle 2015), full sacral and hyoid fusion and full dental eruption (Scheuer and Black 2000).
	Estimated death date	AD 1050-1250, estimated median death date = 1150 (Cessford and Alexander in Robb n.d.). Died pre-1350.
	Burial treatment	Normative burial in All Saints by the Castle parish cemetery (Cessford in Robb n.d.)

Table 71: Key data generated by the 'After the Plague' project pertaining to PSN 746 (includes references for methods and standards used for recording the data)

PSN 746 was a tall, robust male. He is likely to have been born sometime in the early 11th to early 13th centuries and died aged 36-45 years old, ultimately being buried at All Saints by the Castle. In many ways, PSN 746 stands out as being atypical of the population at All Saints. He is the tallest individual measured from High/Late Medieval Cambridge (185cm) and he may have been noticeable walking around Medieval Cambridge. His dentine $\delta^{13}C$ and $\delta^{15}N$ values are quite low for the site, and for High/Late Medieval Cambridge in general and he has unusually low enamel carbonate $\delta^{13}C$ values, indicating his childhood diet was not typical of others buried at All Saints. His $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values place him outside of Cambridge during his childhood. In Britain, his values mean he could have grown up in areas such as East Wales, the Midlands, the North East or Scotland, although some very small areas around more local areas, such as Ely and Lynn could also match these values. All Saints is likely to have been a parish with a migrant population who may have come to the area for employment or trade. He could have been employed doing manual labour, such as an agricultural labourer, stonemason or even a soldier, given the proximity of his parish to the Castle.

9.5.4 PSN 912

PSN 912 [skeleton 2446]		
Basic Information	Skeletal condition	75-100% complete, good preservation, although long bones are very root etched (Brickley and McKinley 2004, Mitchell and Brickley 2017)
	Sex	Female: overall os coxae features = female (Phenice 1969; Buikstra *et al.* 1994; Brickley 2004; Ferembach *et al.* 1980); mandibular features = ?female; overall skull features = female (Keen 1950, Ferembach *et al.* 1980, Buikstra and Ubelaker 1994, Schwartz 2007); aDNA = XX, female (Skoglund *et al.* 2013)
	aDNA (human)	mtDNA: K1c1 (Andrews *et al.* 1999, Kloss-Brandstätter *et al.* 2011), predicted blue eyes dark blonde/brown hair, intermediate skin (Walsh *et al.* 2014, 2017, Chaitanya *et al.* 2018)
	Assigned social group	Rural female
Childhood and growth	Approx. birth date	AD 947.5-1117.5 (estimated from death date minus median age at death)
	Childhood pathology	None present
	Childhood diet (isotopes)	Dentine collagen $\delta^{13}C$ = -18.6‰, $\delta^{15}N$ = 11.8‰, enamel carbonate $\delta^{13}C$ = -11.4‰ *(Rural female means: dentine collagen $\delta^{13}C$ = -19.3‰, $\delta^{15}N$ = 11.5‰, enamel carbonate $\delta^{13}C$ = -12.6‰)*
	Final stature	152.3cm, based on L femur length of 38.6cm (Trotter and Gleser 1952) *(Cherry Hinton female mean = 163.5cm, min = 149.1cm, max = 174.5cm)*
Adulthood	Indices	Crural index = 78.7 (Schwartz 2007)
	Entheses	Very substantial pectoralis major attachments- the anterior of both clavicles appeared scoops
	Osteoarthritis	R.hand (Brothwell 1981, Rogers and Waldron 1995)
	Trauma	None reported
	Other pathology	Maxillary sinusitis (lamellar and spicules) (Boocock *et al.* 1995), healed periosteal new bone growth (Ortner 2003)
	aDNA (pathogen)	None reported
	Dentition	13 teeth present, 5 tooth lost ante-mortem, periodontal disease present = 3/moderate (Ogden 2007), calculus present = 1/minor (Brothwell 1981), periapical lesion present, interproximal caries on roots, impacted right maxillary canine tooth (Hillson 1996)
	Adult diet (isotopes)	Rib collagen $\delta^{13}C$ = -19.8‰, $\delta^{15}N$ = 9.4‰ *(Rural female means: rib collagen $\delta^{13}C$ = -19.6‰, $\delta^{15}N$ = 11.7‰)*
	Mobility (isotopes)	Enamel carbonate $\delta^{18}O$ =-4.63, no enamel $^{87}Sr/^{86}Sr$ data *(Rural female enamel carbonate $\delta^{18}O$ mean = -4.8‰)*
Death and burial	Age at Death	Likely age range 46-59yr, median age 52.5yr, broadly 'old adult', based on pubic symphysis = 5 (Brooks and Suchey 1990), auricular surface = 4 (Buckberry and Chamberlain 2002), full clavicular, spheno-occipital, sacral fusion and full dental eruption (Scheuer and Black 2000).
	Estimated death date	AD 1000-1170, estimated median death date = 1085 (Cessford and Alexander in Robb n.d.). Died pre-1350.
	Burial treatment	Normative burial in Church End Cherry Hinton cemetery (Cessford in Robb n.d., Cessford and Slater 2014)

Table 72: Key data generated by the 'After the Plague' project pertaining to PSN 912 (includes references for methods and standards used for recording the data)

PSN 912 was a relatively short woman, who was likely to have had blue eyes and brown hair and lived to a reasonably old age of 46-59, with few physical signs of ill-heath. PSN 912 was born around AD 950 to 1110. She probably spent her life in a rural environment, ultimately being buried in Cherry Hinton. This period spans the transition from the Early Medieval to the High Medieval period and she may have lived through the Norman Conquest, experiencing a change in the ruling elite, although it is debatable how much this may have filtered down to her everyday life. In her early life, her diet was potentially different to her contemporaries. Her dentine $\delta^{13}C$ and $\delta^{15}N$ values were higher than the mean for others at Cherry Hinton, indicting perhaps she had access to more marine proteins than most rural individuals. There are no signs of nutritional or environmental stress factors during her childhood on her skeleton but her final height was much shorter than other rural women, which could indicate that something inhibited her growth during childhood. Her upper body shows signs of strong muscle development, which may be linked to agricultural work. In later life she also developed arthritis in her right hand, which may also be a consequence of manual labour. The distinctive feature about PSN 912 is the dramatic decline in her $\delta^{13}C$ and $\delta^{15}N$ values between her childhood and her later adult years. Her rib $\delta^{15}N$ values are the lowest recorded of any High/Late Medieval adult analysed and she has the lowest human-faunal offset rib values (2.4‰) of any High/Late Medieval adult female, which is below the expected trophic level difference for an individual eating an omnivorous diet (3-6‰). This suggests a dramatic change in her diet from her childhood, moving to one that must have been largely plant-based. There could be several explanations for this - firstly, she could have suffered from an ailment that prevented her from eating a varied diet. She does show a loss of 18% of her teeth during life, as well as evidence of caries, calculus and periodontal disease, although these are not necessarily any more severe than the average rural Medieval person. Another explanation could be poverty, leading to a reduction in meat consumption. A third possibility, although perhaps unlikely, is that this woman chose to consume a frugal, plant-based diet for religious purposes, as discussed in Chapter 2. Either way, her low $\delta^{15}N$ values do not attest to starvation, and she did not show any severe pathologies or skeletal evidence of nutritional deficiencies when she died as an older adult sometime between AD 1000-1170.

9.6 Summary

Isotope analysis is a powerful tool in archaeology and has added much to the understanding of High/Late Medieval Cambridge and the surrounding area. It has added to the archaeological and historical evidence to enhance the general characterisation of diet in the period, particularly documenting increased animal and/or marine fish consumption. Food and food procurement are a fundamental part of life and so the evidence has also enhanced knowledge of social stratification and confirmed that despite the small geographical area of study, many groups had characteristic dietary traits indicating differential access and consumption of foodstuffs. Isotope analysis has also added to knowledge of migration during the period, identifying a few individuals who almost certainly did not spend their childhoods in Cambridge, adding to our understanding of immigration to the town and connections that Cambridge had with the wider Medieval world. The human data, however, has not demonstrated convincing temporal trends within the High/Late Medieval period, and there is little evidence of considerable changes in diet or mobility after the Black Death.

The real advantage of isotope analysis is that it allows for multiscalar interpretations – it has allowed for analysis at a town level, which can be compared to other sites, it has allowed for analysis at a group level, comparing individual cemetery populations and associated social groups and it has allowed for analysis at an inter- and even intra- individual level. This multiscalar information is invaluable and provides direct, comparable information about what individual people across the social spectrum were actually consuming and where they were from, steps in interpretation that are often not possible using historical and archaeological evidence alone, except in exceptional circumstances, often reserved for unusual and/or high-status individuals (e.g. in biographies, wills, accounts etc). Isotope analysis has therefore added much to the knowledge of direct human experience of life in Medieval Cambridge.

Of course, isotope analysis is not without its limitations and this study has encountered well-known problems. In terms of available material, this thesis has demonstrated the difficulty in analysis of multi-factorial datasets and how to compare data with multiple possible dependent variables. This thesis has demonstrated the difficulty of interpreting temporal change, indicating that robust temporal analysis may only be possible in an example of a relatively stable, well stratified cemetery population which spans a considerable time period.

Specific to this project, it should be acknowledged that several groups that may have made up a significant minority of the population of Cambridge are absent. Conspicuously absent are individuals explicitly associated with a college as well as female members of a religious order. The Jewish population is also not represented, neither are other types of religious orders, and those buried in the Leprosy Hospital. These are all potentially important and distinct groups and their absence from the analysis means that while the dataset is considerable, it is not truly representative of the whole town.

This thesis has also highlighted the inherent limits of interpretation that can be achieved using isotope data. The ultimately crude nature of carbon and nitrogen isotope analysis and the relatively niche areas of diet that the isotopes can inform about, mean many nuances are largely invisible, such as the distinction between primary and secondary animal products, preferences for different types of meat rather than greater quantities of meat, and contributions of various other components of diet, such as fruit and vegetables. The dependence of the interpretation of mobility isotopes on good baseline data of bioavailable isotopes is also a limitation, although this has partly been overcome by the large dataset in this instance. Areas with relatively homogeneous geology, such as Cambridge, lead to limitations in interpretations, particularly in identifying short-distance migration. There are also some more fundamental biological limitations to isotope data that should also be re-iterated. For example, the biological fractionation and routing of these isotopes in various tissues is still not necessarily fully understood, and it is still not fully known how some biological phenomena, such as pregnancy or disease affect isotope values in archaeological tissues, particularly bone collagen. Inherent physiological differences have also not been fully investigated, it is not known, for example, if growth spurts in children, or menopause in older women could affect the isotope values recorded in archaeology. The combination of the inherently large age ranges calculated in skeletal analysis, with the relatively unknown turnover rate of human bone and the averaging effect on the isotopic signal in a human bone means that it is difficult to estimate what period of life an isotope value represents, limiting inferences about adult diet.

While the factors mentioned above do limit interpretations that can be made from isotope data, these are inherent to almost all isotope studies of archaeological material. This thesis has carefully attempted to maximise information that can be gained from the isotope data by taking

a multi-isotope approach, combined with exploratory data analysis and contextualisation with other forms of evidence, without stretching the interpretations of the isotope results beyond their limitations. Following this approach means the data generated in this thesis is still very useful in adding to knowledge of life in High/Late Medieval Cambridge and beyond.



10. Conclusion

This thesis aimed to enhance understanding of what life may have been like in Medieval Cambridge. It aimed to do this by characterising the diet and mobility of the individuals who lived there and exploring whether there was evidence of changes through time, particularly relating to events in the 14th century. This thesis has utilised multi-tissue, multi-isotope analysis to explore the research questions posed, assessing the data by site, sex, social group and various temporal divisions.

10.1 Key Findings

Following the research questions posed in the introduction, the key findings from this thesis include:

No meaningful difference in isotope values pre- and post-1350 or by Medieval century
The isotope data does not show conclusive evidence for temporal changes in human diet or mobility in High/Late Medieval Cambridge relating to events of the 14th century. In particular, the isotope evidence does not show hypothesised increases in animal protein consumption or increased long-distance mobility after the Black Death. This lack of change in the isotope data may in part be because many changes were largely invisible to the isotope methods applied or because the sites chosen may not have been suitable to find these changes but it could also mean that the changes in the Late Medieval period did not affect human diet and mobility as much as may have been assumed. The strontium isotope values at the Hospital provide the only hint of temporal change in mobility, implying that there may have been increased diversity in the origins of the population buried in the post-1350 period. However, the majority of the post-1350 values are all still within the 'local' range so any migration cannot be conclusively proven,

but it was probably short distance. The faunal isotope data provides more convincing evidence of temporal change which may be related to the Black Death, with all taxa showing significant changes in their nitrogen isotope values post-1350, which could relate to changes in animal husbandry.

Large differences in isotope values across the longue durée

Carbon and nitrogen isotope data across the longue durée has shown that changes in human diet between the Early Medieval and the High/Late Medieval period far eclipse any changes within the High/Late Medieval period. The increased consumption of marine fish in the High/Late Medieval period distinguishes it from previous periods and is probably the most significant detectable change in diet in Cambridgeshire.

Differences in isotope values by site

Isotope analysis by site subgroup was the most successful and satisfying way to compare the data. Even within one town and its hinterlands, the site subgroups are relatively distinct in their isotope character, indicating that there was discrete social stratification in Cambridge that influenced diet. In particular, religious influence on diet is clear at sites where the population would have strictly followed rules of fasting and abstinence.

Variable protein consumption in individuals

The isotope data allowed for characterisation of diet, showing that most people were consuming a terrestrial C_3 based diet, with varying degrees of terrestrial and marine protein. Some individuals, particularly at the Hospital of St John, were eating very little animal protein towards the end of their life, perhaps indicating poverty and/or illness. The isotope data has been successful at identifying differential marine protein consumption, identifying those in the Friary as the highest consumers.

Differences in dentine and rib collagen isotope values

Comparisons of dentine and rib carbon and nitrogen isotope values have revealed considerable information about changes between childhood and adulthood diet and individual experience. The evidence suggests that there were differences between childhood and adulthood diet, particularly for those who entered into a religious order. For most living in the town, adult diet

contained more animal protein than childhood diet, but this pattern was not seen in those from the rural site of Cherry Hinton.

High $\delta^{15}N$ values in domestic herbivores

The faunal isotope data in this thesis allowed for a general characterisation of the potential range of isotope values present in the food chain in the past in Cambridgeshire and found evidence of elevated $\delta^{15}N$ in cows and sheep/goats that may be attributed to fenland grazing or crop manuring. This provides indirect evidence of animal and crop management and re-enforces the importance of incorporating faunal values when comparing data.

Oxygen and strontium outliers – 'non-locals' in Cambridge

A small minority of individuals (c.5%) sampled for strontium and oxygen isotope analysis were identified as being unlikely to have spent their childhood in Cambridge. These individuals were demographically diverse, were present across several sites and were present throughout the High/Late Medieval period, indicating that migration was present but cannot be attributed to a particular type of person or event.

Female migration at All Saints by the Castle

Distribution of the oxygen and strontium isotope data at All Saints by the Castle indicates much more diversity in the females than the males. This is likely to be evidence of increased localised mobility in the female population and could be indicative of women moving to Cambridge for work or marriage. This type of subtle observation of the distribution of values is only achievable with a large, systematically sampled strontium isotope dataset, and this largely untargeted approach has rarely been attempted in archaeological isotope studies to date.

Unusual oxygen isotope range

The range of oxygen isotope values seen in the Cambridgeshire data is extremely large and far exceeds predicted ranges for archaeological data and ranges seen in previous comparable studies. The data from this thesis indicates that estimations of variation in oxygen isotope values in East Anglia need to be re-evaluated. On the whole, the oxygen isotope data was the least diagnostic and most problematic in the dataset and the results in isolation provided very little useful information. The results here call into question the utility of oxygen isotopes for this type of archaeological investigation.

10.2 Summary of Life in Medieval Cambridge

In summary, bringing together the isotope evidence generated in this thesis with osteological, archaeological and historical documentary data had allowed for a comprehensive investigation of diet and migration in Medieval Cambridge. The data has revealed that Cambridge was a town comprised of discrete social groups whose diets varied depending on their religious beliefs, social status and sometimes even their sex and age. Fairs and markets brought fish from the sea, which was slowly adopted as a staple food, starting with the religious and social elites. People experienced changes in their diet throughout their lives, with some entering into religious orders which dictated meals and others perhaps falling on hard times, struggling to afford meat or fish. Rural people may have had different experiences to those living in the town, eating less meat and fish but perhaps being much more self-sufficient while those in the town were reliant on imports to supply key food items, as well as more exotic luxuries. Immigration to Cambridge was not uncommon, with people arriving for education, employment and marriage. There may have been a steady flow of relatively local migrants from the surrounding counties, as well as people from further afield, with the occasional long-distance migrant perhaps travelling from places such as Scandinavia. Migration of women may have been commonplace, with women travelling from the local region to settle down in the Cambridge parishes. Friars from Cambridge may have started out as adolescents in local establishments before travelling around the country and beyond, but it seems they tended to return and retire near to their childhood homes. In summary, Cambridge appears to have been a socially diverse, if stratified town. Historical accounts and archaeological evidence attest that social and economic changes occurred throughout the High/Late Medieval period but these did not have a singular dramatic effect on the population. Perhaps the relatively unusual social structure of the town, with the university, guilds, religious orders and strong trade links meant that people were relatively 'buffered' to change? Perhaps individual circumstances dictated personal experience. Maybe tangible dietary changes were small for the average person - the quality of bread or cuts of meat may have improved but the day-to-day structure of the diet was largely similar. Maybe just a few more people arrived from local villages or further afield, or only certain areas experienced immigration or emigration. Either way, temporal changes that may have occurred in Medieval

Cambridge are both imperceptible to isotope analysis and potentially less dramatic than change across the longue durée.

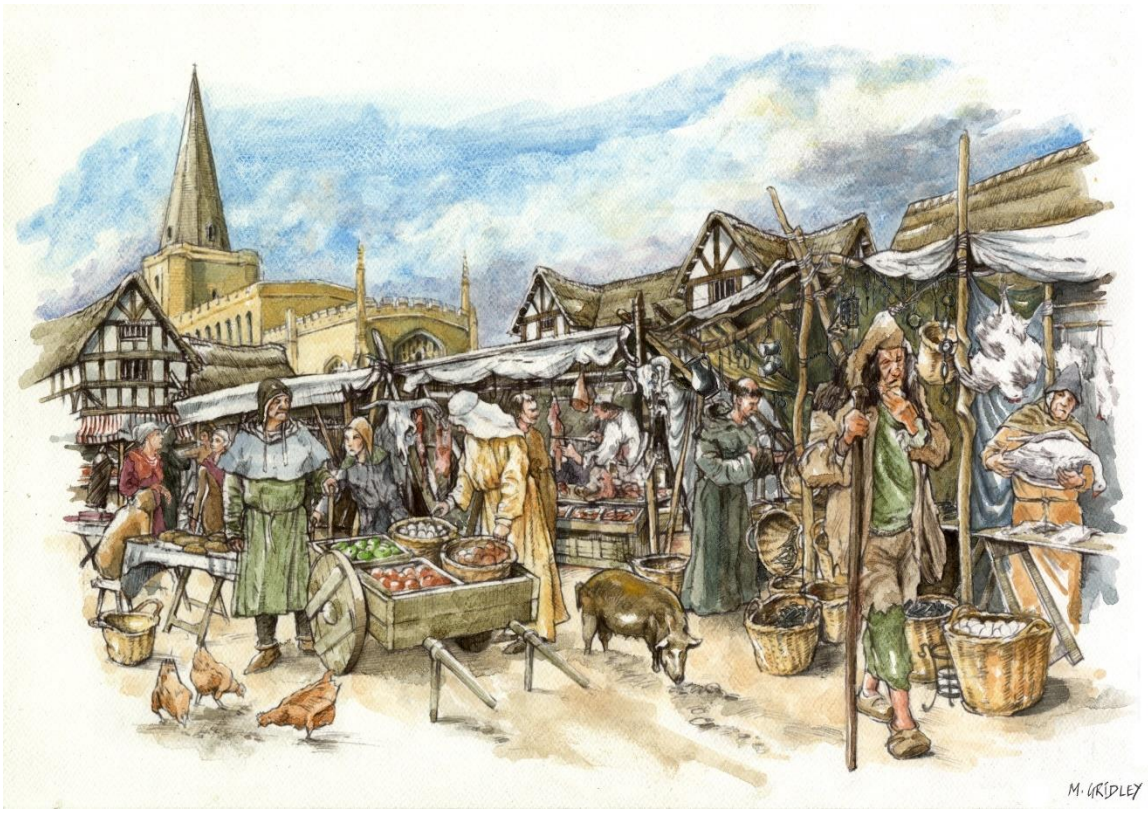


Figure 132: Artistic impression of Cambridge Market Square in the High/Late Medieval period (produced by Mark Gridley for the 'After the Plague' project)

[Permission to reproduce the illustrations by Mark Gridley has been granted by John Robb, Principal Investigator of the 'After the Plague' project.]

10.3 Reflections on Methodology

This thesis has employed some novel approaches to the collection and analysis of isotope data. The large amount of multi-tissue, multi-isotope data generated from a small geographical area almost certainly makes this one of the highest resolution isotope studies carried out in Britain to date. This thesis has demonstrated the wealth of knowledge that can be gained from intensely studying a single area, reducing issues of geological and geographical disparities which are often encountered in studies comparing isotope data from multiple groups. However, it has highlighted that some problems inherent to archaeology, such as missing data, bias in the dataset and small sample sizes as a result of sub-setting, are still present and difficult to

overcome. Nevertheless, this thesis has demonstrated the utility of exploratory data analysis and has applied new techniques of data representation that have not yet been commonly adopted in isotope analysis in archaeology. Based on their success, I highly recommend that these approaches are more widely applied. This thesis has also taken a novel approach in the sampling of strontium isotopes, selecting a more representative sample, rather than picking 'interesting' cases. Although time consuming and relatively expensive, this has proven to be a successful strategy, particularly as individuals which may have been expected to be isotopically diverse, such as the Friars, actually show very little variation and conversely, individuals who turned out to have unusual strontium isotope values often looked 'normal' by any other measure. This has allowed for a much more robust evaluation of the outliers and provides a much more population-wide estimation of the scale of detectable migration. Finally, the methods employed in this thesis have demonstrated that through careful planning, it is possible to obtain multi-tissue, multi-isotope data, as well as aDNA data from a single tooth, minimising destruction of archaeological material. As sampling for destructive scientific techniques is continuously increasing in archaeology, this single tooth approach is recommended.

10.4 Further Research

With such a large dataset, there is much more work that could be carried out on the data presented in this thesis. For example, the application of more sophisticated statistical analyses, such as multi-level modelling, could tease out further patterns and better account for the nested nature of the data. Cluster analysis and application of rKIN (Kernel) Isotope Niche Estimation (Eckrich *et al.* 2020) could be used to test how truly isotopically different the various groups in Cambridge are. Bayesian modelling of likely birth and death dates have been calculated for individuals at the Hospital only and this data could be used to investigate temporal change at the Hospital in more detail to see if patterns are apparent at a finer temporal scale. It was deemed beyond the scope of this thesis to fully investigate changes in isotope values by life stage, and so this could also be investigated further, and may complement investigations into the isotope data by sex in particular. Finally, further comparisons with new datasets could be invaluable. Unfortunately not published in time to be included in this thesis, Stoke Quay, Ipswich is an example of a single cemetery site with skeletons that span the whole High/Late Medieval period, including the 14th century and the isotope data from these could provide

insights into temporal change within one population that could be contrasted with the findings here.

More broadly, there is plenty of scope for the data presented in this thesis to be used for comparisons and baselines. This dataset contributes to the relatively small but ever-expanding isotope dataset for the High/Late Medieval period in Britain, as well as expanding the isotope dataset through time for Cambridgeshire. While the focus has been on the human isotope data, this thesis has generated a large faunal dataset, and it is hoped this can provide baseline information for future studies, as well as information about animal diet and husbandry. In particular, this thesis has generated a large amount of new $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ data for an area which previously had very little – this adds to our knowledge of the bioavailable strontium signature of Cambridge and crucially, it brings into question estimates of the expected range of $\delta^{18}O$ values in Britain, indicating they may need to be re-evaluated, particularly for East Anglia. Hopefully this new data can be incorporated into future biosphere mapping projects.

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