REASSESSING THE SCOTTISH MESOLITHIC-NEOLITHIC TRANSITION: QUESTIONS OF DIET AND CHRONOLOGY

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MARCH 24, 2018

SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

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Acknowledgements

There is a long list of people I need thank for their contributions to this work. First and foremost are my supervisors, Dr Philippa Ascough, Professor Gordon Cook and Dr Iona Murray. I must also thank the AHRC and Historic Environment Scotland for funding this research.

To the SUERC Radiocarbon staff - Elaine, Phil, Brian, Kerry and the technicians - thank you for putting up with me while I hammered bones into tiny pieces and covered myself in blood and bone marrow.

I am also grateful to Ricardo Fernandes, the creator of FRUITS, for providing so much helpful training and advice on the programme.

Samples for this research were kindly provided by Alison Sheridan of National Museums Scotland, Jane Flint of Glasgow Museums Research Centre, Clive Bonsall of the University of Edinburgh, Cath parker, Sheena Fraser, Julie Dougans, and Historic Environment Scotland.

Thank you to my colleagues at LEADS, especially to Jennifer, Andrew, Scott, Iro and Elina, for the help and support while I wrote up my thesis.

It was a pleasure to work with my fellow PhD students during my time at SUERC. Sevi, Pete, Ana and Ross. The mutual support between us all was invaluable. Seriously guys.

Finally, a special thank you to Helen Kinch for being Helen Kinch, to Iain Murdoch for going over and above the call of duty of a laboratory technician, and to my Mum for giving birth to me so that I could eventually write this thesis.

This thesis is dedicated to my Dad and my Gramps who always nurtured my love for learning.

Abstract

The purpose of this research was to broaden our knowledge of the dietary changes and timing of the Mesolithic-Neolithic transition in Scotland. Despite the rich number of archaeological sites around mainland Scotland and the Orkney Isles that date to the transition period (c.4000 to 3600 BC), bones of humans and especially of fauna are rarely recovered. This lack of skeletal material necessary to investigate individual human diet has resulted in a gap in our understanding about dietary changes that occurred during the transition from a hunter-gatherer lifestyle to farming. One of the most widely used and reliable scientific tools available to investigate ancient diet is $\delta^{13}C$ and $\delta^{15}N$ isotope analysis; however, this technique requires samples of human bone and also a representative sample of bones from animals from the same spatial and chronological context as the humans to form an isotopic baseline. Studies of dietary change during the Scottish Mesolithic-Neolithic transition so far have largely relied on poor quality baselines to interpret the diets of the relatively small number of humans recovered from this period. A solution was therefore required in order to ensure that interpretations of dietary change during this time that employed stable isotope analysis of bone collagen were better defined and more secure.

In addition to the problems of interpreting changes in the diet, there are questions surrounding the timing of the Scottish Mesolithic-Neolithic transition as well. The dietary changes were characterised by replacing marine protein with terrestrial animal protein, however we are uncertain as to how fast and complete this shift in diet was. There is long-standing debate regarding how important marine protein was in the early Neolithic diet. If marine protein was only a minor component of the diet, this would be undetected by traditional interpretations of stable isotope data. However, the radiocarbon ages of the bone collagen of these humans may be affected by oceanic ^{14}C. Ancient marine derived carbon in human bone collagen is on average c.400 years older than terrestrial carbon, resulting in the need to correct the ages of mixed marine/terrestrial samples for this Marine Reservoir Effect. Undetected marine protein in the Neolithic diet would result in human bones being assigned radiocarbon dates that are older than the true age of the sample. An improved method of interpreting stable isotope data from bone collagen was therefore sought to address these questions of timing in the Scottish Mesolithic-Neolithic transition.

$\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ isotope analysis was employed on human and faunal bones from Mesolithic and Neolithic sites predominantly in Orkney and the west coast of Scotland.

Isotope faunal baselines were supplemented, where appropriate, with modern faunal samples. The abundance of marine and terrestrial resources in the human diet was modelled using the Bayesian mixing model, FRUITS (food reconstruction using isotopic transferred signals). Where marine protein was detected in the human diet, the radiocarbon dates of these samples were calibrated using the mixed marine/terrestrial radiocarbon calibration curve and compared against previously calculated dates, where these were available.

It was possible to supplement marine faunal isotope baselines with modern marine samples; however, modern terrestrial samples were unsuitable analogues. $\delta^{34}S$ was also found to be an unsuitable proxy for diet in this research. Small amounts of dietary marine protein were detected in the majority of Neolithic humans; however, marine consumption did not have a significant effect on the radiocarbon dates of these individuals. The key finding of this research was, therefore, that the transition from the Mesolithic lifestyle to the Neolithic in Scotland was a lengthy and gradual process, contributing to the debate regarding the nature of the transition. The chronology of the transition that has been previously established by radiocarbon dating is secure: while modelling the isotope data in FRUITS resulted, in most cases, in a greater age range in calibrated radiocarbon dates, they were not erroneously old, as initially predicted.

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Chapter 1: Introduction

1.1 Introduction

This chapter presents the aims and objectives of this research. The fundamental problems associated with recreating diet in the Scottish Mesolithic and Neolithic are outlined, before the research aims and methodological approach of the thesis are explained. The chapter concludes with an outline of each chapter of this thesis.

When referring to dates in this thesis, references to calendar dates are stated as BC. Radiocarbon dates are presented in both the uncalibrated radiocarbon age BP (where available) and in the calibrated date cal BC. This is so that the thesis provides the appropriate raw data for reproducibility and also the context which a calibrated date provides. All new radiocarbon dates have been calibrated using OxCal 4.3 and the IntCal13 and Marine13 radiocarbon age calibration curves (Bronk Ramsey, 2009, Reimer et al., 2013).

1.2 Research aims and objectives

The overall aim of this thesis is to improve our knowledge of dietary changes in the Scottish Mesolithic-Neolithic transition c.6000 years ago, as well as improving methods used in stable isotope analysis for palaeo-dietary reconstruction. The need for this research comes from a lack of clear understanding as to how important marine resources were in the Scottish Neolithic. It is confidently asserted in archaeology that dietary habits changed from a large dependence on marine fish and shellfish in the Mesolithic, to a heavily terrestrial resource-based diet in the Neolithic; however, the extent to which marine produce continued to be utilised in the Neolithic not well understood. It is important that we pursue an answer to this so that we can better understand the nature of the Mesolithic-Neolithic transition.

The methodology adopted was as follows:

- Produce $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ isotope measurements from human and faunal bone collagen samples from Mesolithic, Neolithic and modern Scottish sites.
- Assess the viability of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ measurements from modern faunal analogues to supplement ancient isotope dietary baselines.
- Measure the $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values of modern faunal bone collagen and flesh to produce local and specific tissue isotope offset values required for FRUITS (food reconstructions using isotopically transferred signals) dietary reconstruction models.
- Model the appropriate data in the dietary modelling programme FRUITS to produce relative estimates of marine and terrestrial resources in the human Mesolithic and Neolithic diet.
- Where necessary, use the estimates of marine resource consumption produced using stable isotope analysis and FRUITS to calibrate human bone collagen radiocarbon dates, using the mixed marine/terrestrial calibration curve to correct for potential marine reservoir effects (MREs).

In order to:

- Offer a reassessment of dietary and subsistence changes across the Scottish Mesolithic-Neolithic transition.
- Provide recommendations for best practice methodology for producing accurate and precise ancient dietary reconstructions using stable isotope analysis and FRUITS, from sample selection, to pre-treatment methods to the analysis and interpretation of isotope data.
- Allow the work to be used by researchers to supplement isotope baselines and correct radiocarbon dates for any archaeological site in Scotland.
- Provide a more secure chronological basis for the Mesolithic-Neolithic transition in Scotland.

1.3 Thesis outline

This thesis is comprised of seven chapters. Chapter two, which follows, comprises a review of the literature in the field of archaeology on the subject of the debates surrounding the nature of the Mesolithic-Neolithic transition. Chapter three considers the scientific literature on the applications and limitations of stable isotope analysis for reconstructing ancient diet and radiocarbon dating for establishing the chronology of human remains. Chapter four details the materials used and protocols applied to samples in this research, and the results of the analytical work are detailed in chapter five. Chapter six discusses the data in detail, providing an interpretation of the measurements and linking these to the literature. Finally, this thesis is concluded in chapter seven, with a series of recommendations and an indication of the scope for future investigations.

Chapter 2: The Nature and Timing of the Mesolithic and Neolithic Periods in Europe and Scotland

2.1 Introduction

This chapter will provide the background and context to the time period this thesis is concerned with, i.e. the transition from the Mesolithic to the Neolithic periods. Arriving at universally accepted definitions of these periods has been problematic (Chapter 2.2). The study of the Mesolithic period has suffered because of the lack of consensus in the past regarding its definition. The Neolithic period has been difficult to characterise because of the diverse nature of the 'Neolithic package'. In addition to these issues, the nature of the Mesolithic-Neolithic transition is still being questioned because, until recently, the two periods were investigated separately. Our perception of the Mesolithic culture has changed from considering communities as struggling and simple to understanding they were, in fact, adaptable and complex.

Now that the Mesolithic-Neolithic transition is viewed much more as a fluid and continuous period in prehistory, our understanding of the drivers of cultural change have become clearer (Chapter 2.3). A changing climate has been identified as a possible factor in the origin and spread of agriculture (Chapter 2.3.1). Significant climatic shifts may have encouraged the movement of farming through Europe. In Scotland, the decline of woodland and the exploitation of clearings for plant cultivation was the result of a changing climate and direct human interaction. While a changing environment coincided with the Mesolithic-Neolithic transition, archaeological evidence shows that communities were the foremost influence of the spread of the Neolithic.

This chapter emphasises the importance of people as the driver of change (section 2.3.2), beginning with our changing perception of Mesolithic culture from communities being marginal, to understanding they were adaptable and complex societies in their own right. Examining and characterising material culture, we can see how the nomadic hunter-gatherer lifestyle of the Mesolithic moved to the sedentary agricultural lifestyle of the Neolithic. Whether this change happened as a result of the movement of people or ideas has been the subject of extensive debate. New advances in aDNA techniques have largely settled these

questions of 'adoption or migration', and have allowed the study of the Mesolithic-Neolithic transition to move on to more nuanced questions about its nature.

Finally, this chapter summarises and reviews the literature to date that has informed the key question asked in this thesis: how did diet change from the Mesolithic to the Neolithic periods (Chapter 2.4)? There have been extended discussions about the importance of marine resources in the Neolithic, with stable isotope analysis of bulk bone collagen showing a sudden and permanent abandonment of seafood, and archaeological evidence suggesting that shellfish and some fish continued to be useful into the Neolithic. Current methods of dietary reconstruction must be refined in order to shed light on this longstanding debate.

2.2 Defining the Mesolithic and Neolithic Periods

2.2.1 Towards a definition of the Mesolithic period

In order to sufficiently understand the context of this research, it is necessary to define the time periods considered. The Mesolithic period has had several distinct definitions since its first use in the 19th century (Westropp, 1866). Scholars identified the need to separate the spear and hand axe technologies of the early Palaeolithic in glacial Europe from the microlith producing hunter-gatherer cultures of the post glacial period (c.10,000 BP). Since the introduction of the term 'Mesolithic', the connotation has developed from vague chronological definitions in the first half of the 20th century (Westropp, 1866, Childe, 1927: p.20, Clark, 1936: p.xiv, Gabel, 1958), to a more sophisticated classification which accommodates an economic and cultural typology with some chronological constraints (Binford, 1968: p.313, Kozlowski, 1973: p.332, Clark, 1980: p.4, Price, 1983, Zvelebil, 1986). The current accepted chronological definition of the onset of the Mesolithic period is 10,000 BP, marking the glacial recession in Europe (Mellars, 1981). The end of the Mesolithic is marked by the appearance of agriculture (i.e. the use of domesticated plants and animals), and since this occurred at different times across Europe, the chronological boundary for the Mesolithic-Neolithic transition is between 6500 and 3500 BC (Price, 1987).

Price (1987) connected the initially ambiguous and fluid nomenclature, which was associated with the Mesolithic, with the tendency for the period to be overlooked in archaeology. Changing classification of the period and regional variations in definitions

across Europe has resulted in little cohesion in the study of the Mesolithic. While the term 'Mesolithic' has been accepted by most of Europe to denote the period between 10,000 BP and the onset of agriculture, a minority of researchers continue to talk about the 'Epipalaeolithic' when referring to the same time period, and in some cases refer to an Epipalaeolithic-Neolithic transition (Colledge, 2001, Linstädter, 2008, Mulazzani et al., 2010, Morales et al., 2013). Vermeersch (1999) discusses a separate Epipalaeolithic and Mesolithic without clearly defining the timescales these terms represent. It is difficult to carry out comparative European studies of a time period which does not have a universal definition; this thesis, therefore, uses the term 'Mesolithic', not 'Epipalaeolithic'.

2.2.2 Defining the Mesolithic-Neolithic transition

This discord extends to the study of the Mesolithic-Neolithic transition, because, until recently, there has been a dichotomy between the two periods whereby they were studied separately, and not as a continual development of human prehistory. Thomas (1988) noted that the Mesolithic and Neolithic cultures have been viewed in vastly different lights and this has harmed the study of the transition between them. In the past, Mesolithic societies were viewed as passive, adapting their lifestyles according to the changing climate, and the Neolithic was perceived as a more sophisticated goal-orientated culture (Armit and Finlayson, 1992, Thomas, 2004). This may be a result of the Mesolithic period traditionally being viewed as a poverty stricken period where human-kind faced a daily struggle to survive (Childe, 1942: p.43, Price, 1987); however, the reality is that the Mesolithic culture was far more technologically and socially advanced than the preceding upper Pleistocene hunter-gatherers. These opposing views of Mesolithic and Neolithic culture may also stem from a simplification or misunderstanding of dominant theories about the Mesolithic-Neolithic transition. For example, Cummings & Harris (2011) distilled Sheridan's argument for colonisation as the driver of the Neolithic by describing the new farmers as the people who "made decisions about whether to move, whether to exchange animals and whether to train local people in new kinds of practices" (Cummings and Harris, 2011): this implies that the Mesolithic communities in Sheridan's model were viewed as docile and submissive: this is something that Sheridan vehemently denies in her reply to the paper (Sheridan, 2011).

Our current understanding is that Mesolithic people were sophisticated and resourceful enough that the lifestyle was not immediately replaced by sedentary farming on the arrival

of the Neolithic, and that the two lifestyles co-existed for far longer than previously believed. Evidence of Mesolithic lifestyle and subsistence in Scotland is concentrated almost exclusively on the coast, and shows that communities were diverse and complex (Hardy and Wickham-Jones, 2002). Mesolithic communities are understood to have been mobile hunter-gathers, indicated by the shared material culture at a large range of sites (Hardy and Wickham-Jones, 2002). Analysis of human skeletal remains from Europe gives us some indication of designated social roles in the Palaeolithic and Mesolithic: remodelling of muscle attachment areas of the upper limb bones revealed potential sexual division of labour, with males more likely to have used throwing weapons extensively throughout their lives (Villotte et al., 2010).

Unlike the Neolithic lifestyle, which was characterised by sedentary living, Mesolithic people relied on several sites to provide everything required to sustain a community. Sites were exploited on a seasonal basis, with temporary camps often used for a specific purpose, for example hunting, foraging or gathering stone for tools (Deith, 1983). The seasonal use of sites in Scotland has been revealed by the $\delta^{13}C$ and $\delta^{18}O$ analysis of growth rings in shells from shell middens (Deith, 1983, Deith, 1986), and by scanning electron microscope analysis of plant remains (Dark, 2013). The more common method of using faunal remains is to identify the seasonal use of sites, for example by identification of shed antlers of red deer (Fraser and King, 1954), or by tooth eruption of mammals as demonstrated by Legge and Rowley-Conwy (1988), is not applicable in Scotland because of the sparse nature of surviving material (Kitchener et al., 2004).

The mobility of Mesolithic communities is connected to their subsistence strategies: moving to different sites was essential to be able to source all of the food, fuel and other resources that were needed. Mesolithic populations sourced food from the land and the sea, utilising a large range of tools to aid them. Examples of harpoons have been found at sites at the Inner Sound of Scotland, and the fish remains at many sites indicate that Mesolithic people were capable of deep sea as well as in-shore fishing (Hardy and Wickham-Jones, 2002). Vast shell middens indicate the large scale at which marine resources were exploited (Álvarez et al., 2011). Stone tools and terrestrial animal remains are common, and indicate the hunting of large mammals such as deer and aurochs (Connock et al., 1991, Bonsall et al., 1992, Schulting and Richards, 2002, Bartosiewicz et al., 2010). There also is tentative evidence from England that dogs may have been domesticated as early as 9500 BC (Clutton-Brock and Noe-Nygaard, 1990).

In addition to evidence of animal consumption, some plant remains also survive to indicate the variety of vegetation in the Mesolithic diet. The ubiquitous presence of hazelnut shells in the Scottish Mesolithic shows how communities foraged and used the land (Schulting and Richards, 2002, Dark, 2013). Peat analysis indicates that the Mesolithic in Arran, off the coast of west Scotland, involved the purposeful manipulation of the land by burning. Pollen and charcoal were identified in peat cores from Machrie Moor and were used to map the prehistoric landscape of Arran, including an extensive episode of burning which resulted in a decline in woodland cover from around 5900 BC, extending into the Neolithic (Robinson, 1983). It has been hypothesised that advances in land manipulation, such as at Arran, is evidence for the cultivation of wild plants, paving the way for the Neolithic agricultural lifestyle (Zvelebil, 1994). This hypothesis is backed up by a large-scale review of pollen analysis as evidence for land manipulation across 39 Mesolithic sites in Scotland (Bishop et al., 2015). Current understanding of the Mesolithic use of plants is that foraging was widely employed, but that human interaction with the environment may have (inadvertently or not) shaped the landscape (Mellars, 1976, Bishop et al., 2015).

Studies have examined the differences between the Mesolithic and the Neolithic lifestyle to determine the nature of the Mesolithic-Neolithic transition. Emphasis has been placed on a sharp shift between the Mesolithic and Neolithic, with seemingly clear junctures between the two. Stable isotope measurements of human bone collagen from Mesolithic and Neolithic populations have been used to show that marine resources, which were a large staple of the Mesolithic diet, were entirely and permanently rejected after the introduction of farming (Richards et al., 2003, Richards and Schulting, 2006). It is more commonly recognised today that the boundaries between these two periods are blurred (Borić et al., 2004), and, in some cases, there is evidence for sporadic returns to a Mesolithic lifestyle by Neolithic communities (Montgomery et al., 2013) (see Chapter 6.4), and even the close co-existence of Mesolithic and Neolithic cultures (Hoffman, 2015) (Chapter 2.4).

2.2.3 Defining the Neolithic period in Scotland

The Neolithic period in Europe is recognised as the onset of agriculture, sedentary living and the introduction of ceramics and polished stone tools (Whittle, 2001, Darvill, 2010). The new tool culture of the Neolithic was distinct from that of the Mesolithic – partly because the migration of people brought new ideas and methods, but also because the tools of the

Neolithic served a very different purpose to those of the previous period: agricultural tools such as sickles and axes replaced flint blades and arrowheads for hunting. The production of flint arrow heads and microliths are described as a "lithic signature" of the Mesolithic period (Finlay et al., 2002), and in much the same way, polished stone tools are the signature of the Neolithic period.

The definition of the Neolithic has its issues since not all Neolithic sites contained this Neolithic 'package', and in some areas of Europe, pottery was introduced in the late Mesolithic period, for example at hunter-gatherer sites in Finland (Núñez, 1990), and Russia (Kuzmin, 2002). Thomas (2003) suggested that it is unlikely that polished stone tools were pervasive at the beginning of the British Neolithic, and argues against a homogenous Neolithic 'package' and offers, instead, the term 'repertoire' – a collection of technology and resources which the indigenous populations could select from. This interpretation is particularly sensible for describing the Scottish Neolithic, since there are distinct and diverse 'types' of Neolithic settlement across the country. There are differences between the material culture from the two main site areas in this thesis, the West coast and Orkney. Orkney, for example, has large stone monuments, such as the Ring of Brodgar, that are exclusive to that area (Armit and Finlayson, 1992). West coast cave and shell midden sites have yielded unique microliths and antler tools, leading to the identification of the 'Obanian culture' (Movius, 1942, Bonsall, 1996, Bartosiewicz et al., 2010). As a result of Scottish regional differences in the Neolithic and for the sake of clarity, the Neolithic will be defined in this thesis as a sedentary farming culture – a definition now widely accepted in archaeology.

Constraining a definition of Neolithic is also somewhat complicated by the fact that it spread across Europe from east to west over a period of millennia. So, while the Neolithic began in 8400 cal. B.C in Jericho (thought to be the origin of the European Neolithic) (Gkiasta et al., 2003), agriculture did not reach Scotland until 4000 BC (Bonsall et al., 2002a). The main temporal focus of this thesis is on the transition between the Mesolithic and Neolithic periods in Scotland. In order to highlight changes in culture and subsistence over time, sites from the Mesolithic to the Neolithic periods are examined. The chronology of sites examined in this thesis spans 4500-2800 B.C.

2.3 Drivers of the Transition

2.3.1 Climate change as a driver of the transition

Factors that influenced dramatic and permanent change in human subsistence practices must be considered in order to gain a good understanding of the Mesolithic-Neolithic transition. Since subsistence, whether hunting and gathering or farming, relies so much on favourable environmental conditions, climatic factors have been examined here at key points in the transition to the Neolithic across Europe. Significant changes in temperature and precipitation have been found to coincide with the earliest evidence of farming, with the initial spread of farming to the west, and with the arrival of the Neolithic in Scotland. For the most part, these changes have been shown to be favourable to each of these three events, although the nature of climate shifts in Scotland is debated (Tipping, 1995, Anderson et al., 1998, Macklin et al., 2000, Bonsall et al., 2002b, Langdon et al., 2003, Richards and Schulting, 2006, Schulting, 2010).

The end of the last Ice Age at c.10,000 BP was shortly followed by the earliest indications across Europe of the pre-pottery Neolithic A (PPNA), as defined by Kenyon (1952), at 11,700-10,500 cal BP in the Southern Levant (Kenyon, 1952, Kuijt and Goring-Morris, 2002). This is the first indication of a settled Neolithic culture that grew crops and hunted wild animals (Kenyon, 1955). Pre-pottery Neolithic B populations followed these initial settlements at 10,500-8250 BP, with the earliest examples of animal domestication (Kuijt and Goring-Morris, 2002). As the names suggest, these cultures were defined as Neolithic because of their subsistence practices, but they preceded later ceramic producing groups. It is pertinent that the onset of farming should coincide with the retreat of glacial cover: the warmer temperatures may have made possible the development of agricultural technology and, therefore, the permanent settlement of communities.

Large-scale climate change may have encouraged the spread of the Neolithic culture from its origins in The Fertile Crescent as well as encouraging its inception. At around 8200 BP, proxy records indicate that massive environmental change was produced by a climatic event affecting the Northern hemisphere (Alley et al., 1997, Veski et al., 2004). Ice core and sedimentary records suggest that this change came in the form of sudden altering of oceanic and atmospheric circulation and an influx of freshwater into the North Atlantic from Lake Ammersee (Ellison et al., 2006). The event resulted in cooler, arid conditions, with a relative drop in global temperatures (Alley and Ágústdóttir, 2005). It has been argued that this cold

event was the catalyst that expanded farming cultures from The Fertile Crescent to Eastern Europe as farmers suffered drought and, in response, sought more favourable climates and developed new irrigation technology (Weninger et al., 2006). Despite the chronological correlation of the expansion of the Neolithic and the 8200 BP cooling event, and the knowledge that global climate change can affect population demography, more work is required to prove causality (Budja, 2007).

As the Neolithic culture spread East through Europe, a hiatus in its progress occurred in the 5th century BC. While sedentary farming cultures had reached France by 5400-4900 BC, the earliest signs of the Neolithic in neighbouring Britain, Ireland, Denmark and Sweden are not evident until 4100-3800 BC (Bonsall et al., 2002b). This 'late' introduction of agriculture to these areas was associated with significant climate change in Scotland, England, Netherlands, Sweden and Finland (Bonsall et al., 2002b). There are several lines of evidence that support this assertion. In Mainland Europe, analysis of macro- and microfossils in peat from the Netherlands identified several species of plant and fungi that are characteristic of dry hydrological conditions, indicating a shift away from the typical damp climate of the area (Dupont, 1986). Sediment analyses in Lake Bysjön, Southern Sweden, shows a lowering in the water level and therefore drier conditions between 4800 and 2600 BC (Digerfeldt, 1988). These shifts to drier conditions in inland Europe occur at the same time as a drier climate in Scotland, as indicated by peat bog analyses (Tipping, 1995). This drier climate made the environment more conducive to crop growing and raising animals and, therefore, could arguably have been an important factor in the onset of the Neolithic culture in Britain.

On a local scale, there is debate regarding possible climate changes at the onset of the Neolithic in Scotland. Evidence derived from plant macrofossils and humification data can be used to argue in favour of the theory that Scotland's climate became wetter and colder at 5850 BP (Langdon et al 2003). This is evidence from only one 43 ha site; however, and we should be cautious when applying this to the whole of Scotland. When considering the scope of scientific data Schulting (2010) argues that advocates of the 'drier and warmer' climate change model ignore the evidence against this theory. While some studies suggest this dry period may have begun later (Anderson, 1998) or shifted to wetter conditions sooner (Tipping, 1995, Anderson, 1998), the general consensus is for a shift to drier climate at the transition period which extended into the Neolithic period. Evidence of a warmer environment comes from a variety of sources. Species of beetle were identified in peat that

favour relatively warm climes (Girling, 1984). δ^{18} O analysis of speleothem calcite and the comparison of the width of tree rings suggests that average temperatures in North Europe may have increased by up to 2°C during the transition (Briffa, 1994). Bonsall et al. (2002a) collated previously published peat humification data from Anderson (1998) and data from charcoal, pollen and woodland decline analyses (Macklin et al., 2000) to conclude that a relatively dry period occurred in Scotland at 4100 BC which continued into the Neolithic period until at least 3200 BC.

The overall climate change experienced in Scotland and areas further afield may also be responsible for some of the changes to the landscape during the Mesolithic-Neolithic transition. Woodland, made up of elm, pine and hazel was characteristic of the Mesolithic period; however, tree cover began to decline at approximately 3000 BC. Some have argued that the decline in tree cover and the appearance of larger and more frequent clearings are evidence of human activity; Mesolithic fire ecology was among the first land manipulations to aid subsistence practices by clearing large areas of land quickly and efficiently (Innes and Blackford, 2003). However, charcoal concentrations and pollen data from Oban, Scotland indicate that the changes in plants and trees are as a result of associated climate change (Macklin et al., 2000). Macklin et al. (2000) suggested that trees which were not adaptable to warm climates died off and were replaced by plants which required open space and sunlight and, additionally, that the interpretation of charcoal and palynological records may overemphasise the impact that humans had on the Scottish environment prior to 3000 BC.

The assertion that human intervention alone cannot account for the large-scale decline in tree cover at the onset of the Neolithic is logical. Brown (1997) reconsidered pollen diagrams to challenge the notion that the late Mesolithic landscape was dominated by thick forest. He argued that early farmers most probably opportunistically occupied natural clearings, and so intentional deforestation was much less common than previously thought. This being said, such a large shift in climate towards a warmer and drier environment cannot be ignored as a probable factor in the changes to the late Mesolithic and early Neolithic landscapes across Scotland and Europe. Milder climates are much more favourable when growing crops and raising animals, and therefore must be considered as one of the many inter-connected factors that contributed to the cultural change from hunting and gathering to farming practices.

The Neolithic period is associated with massive changes in lifestyle and subsistence, so its drivers and origins have been an important topic of research for many years. A changing

climate has been identified as coinciding with the Neolithic, and it has been debated as to whether this was the major driving force of agriculture, or if humans were operating outside of climatic influence. Identifying the nuances of these environmental changes has proved difficult. While it is widely accepted that there was a global climate shift to cooler and drier temperatures at 8200 BP that may have been beneficial to the very first agricultural communities in the Middle East, evidence for climate change at around 5800 BP in Western Europe is conflicting. This conflicting evidence may be indicative of small scale climate changes, or of an uncertain chronology in the climate proxies. Further research into climate change in the UK around the time of the transition, including improving the chronological resolution of sedimentary sample sequences, would shed some light on the matter.

2.3.2 Cultural change as a driver of the transition

Though it is clear that climate change was a dominant factor that drove the transition from the Mesolithic to the Neolithic period, there has been an intense and long-standing debate about how exactly the Neolithic package travelled west across Europe. Two schools of thought on the matter emerged, supported principally by Sheridan and Thomas. The latter said that the Neolithic moved via a transfer of ideas and an adoption of the Neolithic lifeway by indigenous populations. The former asserted that the cause of the movement of the Neolithic package was not the transfer of ideas, but the movement of people. Understanding how the Neolithic package spread across Europe is a vital element of understanding the nature of the transition. Evidence supporting each side of the debate has been discussed extensively in the last two decades, and only recently has the question been largely settled in favour of the migration theory through aDNA research.

The ‘indigenous adoption’ theory argues that new farming practices, technologies and social ideals were passed from Britain from Neolithic communities to hunter-gatherer communities. Mesolithic communities then selected aspects of the Neolithic lifestyle to adopt, and for this reason the characteristics of the Neolithic should be described as a ‘repertoire’ as opposed to the popularly used ‘package’ (Thomas, 2003). The evidence to support this idea comes from the diversity displayed in early Neolithic assemblages, and while Thomas accepts that domestic animals originated from Europe, the range of monument types and subsistence practices is characteristic of communities changing their lifestyles as opposed to colonists imposing theirs upon them (Thomas, 2003).

The rapidity of the transition to the Neolithic lifestyle is also evidence in favour of the indigenous adoption model. Stable isotope and radiocarbon evidence shows that the dispersal of the Neolithic lifestyle was very rapid upon its arrival in Britain (Schulting and Richards, 2002, Richards et al., 2003, Richards and Schulting, 2006); this rapid expansion would only be possible through a 'colossal invasion of Neolithic people' (Thomas, 2004). Thomas argues that there is no archaeological evidence for such an invasion and, since it is unlikely that a smaller-scale influx of people would have such a profound effect on Mesolithic lifeways, the Neolithic lifestyle must have transferred to Scotland and the rest of Britain by selective adoption of new technology and subsistence practices by the native population. (Thomas, 2004).

The second school of thought asserted that the cause of the movement of the Neolithic package was not the transfer of ideas, but the movement of people. Migration was offered as the primary vehicle for the spread of the Neolithic, and challenged Thomas' assumptions that Britain was closely connected to continental Europe to allow for the communication and transfer of ideas. Dr. Alison Sheridan was the primary advocate of the Neolithic migration model, and her research included a suggestion of probable migration routes that were taken through Europe to Britain. The 'migration' model criticises the 'indigenous adoption' model for suggesting that the only alternative to Neolithic adoption is a massive invasion of people from continental Europe (Sheridan, 2010). Instead, Sheridan argues for a more nuanced multi-strand model of migration than a single vast invasion, and posits that the uptake of farming by native groups was a consequence of the migration as opposed to a driver of the transition (Sheridan, 2010).

The routes of migration proposed in favour of the 'migration' model are derived from the distribution and chronology of the earliest signs of the Neolithic in Britain and Ireland. Faunal remains, monuments and pottery are utilised to propose an early but unsuccessful migration from France to Ireland towards the end of the 5th millennium BC, followed by a series of migrations, beginning around 4000 BC, to the west coast of Britain and Northern Ireland (Sheridan, 2010). Shortly after, a large-scale movement of people likely took place from mainland Europe to the southern and east coast of Britain and much of Ireland, and a final possible migration to southern England (Sheridan, 2010). This theory is supported by Collard et al (2010), who used radiocarbon dating of Mesolithic, Neolithic and Bronze Age site phases to estimate the density of the population at around the time of the transition. They found evidence of a large increase in Britain's population, beginning in Southern England

and moving North to Scotland (Collard et al., 2010). While this is a different route than that suggested by Sheridan, they remain in support of the 'migration' model of Neolithization, rather that the 'adoption' model (Collard et al., 2010).

The true nature of the onset of the Neolithic in Britain may lie in a grey area between the two models examined here. There are arguments to say that the Neolithic lifestyle did not have to be a result of one model or another, and that the claim that it did is too simplistic. Cummings and Harris (2011) argued that the debate surrounding the Mesolithic-Neolithic transition had become 'stale', 'polarising' and 'unhelpful', asserting that elements from the two radically opposing models should be married to create a new understanding of the transition (Cummings and Harris, 2011). The diversity shown in late Mesolithic and early Neolithic sites are indicative of Neolithic cultures arriving in Britain, and Mesolithic communities selecting favoured characteristics of that culture (Cummings and Harris, 2011). Sheridan's comments in reply to this paper are that the 'migration' model in this case has been misinterpreted to mean a single largescale invasion, as opposed to a multi-stranded migration (Sheridan, 2011). In this way, there is merit to Cummings and Harris' argument about the two dominant models being unhelpful as an explanation of the Mesolithic-Neolithic transition, as both models are open to being interpreted in a simplistic and exaggerated way.

A more complex explanation of the arrival of the Neolithic in Britain is evident through zooarchaeological analysis. The analysis of the variety and distribution of wild and domestic faunal species through the Mesolithic-Neolithic transition of western Europe has revealed a diversity in the species that were utilised by people at the onset of the Neolithic (Tresset and Vigne, 2007). This has been interpreted as an example of how migration was important for physically moving domestic animals to Britain, while native groups influenced the success of certain species by selectively adopting different aspects of the Neolithic package (Tresset and Vigne, 2007). In this model, neither farmer nor hunter-gatherer is portrayed as the dominant instigator of the Neolithic; instead, both community types are credited for shaping the early stages of the Neolithic. This argument is echoed in Garrow and Sturt's multi-methodological approach to investigating the nature of the Mesolithic-Neolithic transition. By investigating palaeoceanographic, palaeoenvironmental and archaeological evidence from Britain, it was concluded that late Mesolithic communities were regularly crossing the ocean between Britain and continental Europe (Garrow and Sturt, 2011). In this way, these communities can be viewed as far more innovative and technologically advanced than they

have been traditionally viewed, and they, therefore, probably had an active role in bringing farming to Britain.

Interestingly, similar findings regarding the Mesolithic involvement in the movement of farming culture have been presented in a high resolution radiocarbon study. Spatial analysis of late Mesolithic and early Neolithic sites in Europe was carried out to map the speed and direction of the Neolithic progression (Gkiasta et al., 2003). This broad view of the Mesolithic-Neolithic transition strengthened earlier findings by similar methods (Clark, 1965). In the 2003 study, analysis was carried out to establish the dominant mechanism for the onset of the Neolithic in a number of countries. Variation was found in the driver for the Neolithic, with countries such as Greece, Italy and Germany being driven by migration, and, crucially, Britain, Ireland and France being driven by a combination of cultural and demic diffusion (Gkiasta et al., 2003). It seems, then, that continental European Neolithization was not the spread of a homogenous package, but was variably influenced by native hunter gatherers and incoming farmers. In Britain, both the Mesolithic and the Neolithic populations shaped the beginning of the Neolithic period.

The debate regarding the likely vehicle for Neolithic movement continued until very recently, when advances in aDNA investigation allowed researchers to study genetic variation across the Mesolithic-Neolithic transition. In a summary review paper examining aDNA analysis of individuals from the Linearbandkeramik (LBK) culture (the first widespread farmers in Europe), Hoffman (2015) shows how the 'migration vs. colonisation' debate has now largely been settled, and suggests that we should turn our focus to other aspects of the Mesolithic-Neolithic transition to keep the study of the period moving forward (Hoffman, 2015).

The aDNA evidence suffers from the same lack of Mesolithic human samples as this research; however, it falls more in line with the 'migration' model than with the 'indigenous adoption' model. aDNA analyses of human bone from across Europe have revealed that Neolithic populations display far more variation in genetic haplogroups than Mesolithic groups (Brandt et al., 2013). Hoffman asserts that such evidence of genetic discontinuity between Mesolithic and Neolithic populations shows that migration was the dominant driver of the Neolithic (Hoffman, 2015). Of course, it cannot be denied that ideas spread with people, and it must be emphasised that the two are not mutually exclusive. Therefore, questions remain regarding the exact geographic origin of the LBK culture which require

further application of aDNA, radiocarbon and archaeological analysis (Hoffman, 2015). It is pointed out though, that novel research about the Mesolithic-Neolithic transition should move away from describing the broad nature of the phenomenon, and begin to focus more on human relationships with material culture and animals (Hoffman, 2015). It is pertinent that this thesis aims to answer detailed questions about the relationship between humans and animals through the lens of diet and subsistence practices.

2.4 Evidence of dietary change in the Scottish Mesolithic-Neolithic Transition

Cultural changes in lifestyle and subsistence practices during the Mesolithic-Neolithic transition are markedly reflected in the diet of human populations at the time. In Scotland, the substantial reliance on marine resources was replaced by the exploitation of terrestrial mammals. While this general shift away from fish and shellfish is unequivocal, and was the dietary trend until the Medieval period in Britain, the role of marine resources in the early Neolithic has been heavily debated. While some academics have argued for a complete and immediate replacement of fish and shellfish with terrestrial animals, others have shown examples of minor or temporary marine contributions to the early Neolithic diet. The strength of this debate lies in the nature of the evidence used to demonstrate dietary habits, and the issue is that the two mostly commonly used methods, archaeozoological remains and stable isotope analysis, are at odds with one another (see Chapter 3 for a review of stable isotope analysis as a tool for reconstructing diet).

The debate surrounding the ways in which dietary habits altered during the Mesolithic-Neolithic transition is centred on the evidence from the archaeology and the evidence from stable isotope analysis: the two offer different explanations of how important fish was as a dietary resource in the Neolithic. Debates between academics are not uncommon, as one side argues the case for animal remains on Neolithic sites and the other argues for the isotope results of human individuals. Both, of course, are correct in their interpretation of the data, however both cannot be accurate representations of events. The conflicting archaeological and stable isotope data from the Scottish Mesolithic-Neolithic transition has resulted in twenty years of academic debate about the role of marine resources at the onset of the Neolithic, the highlights of which are summarised here. If we examine the archaeology, the presence of shell middens and fish remains in the early Neolithic at sites such as Carding Mill Bay and Raschoille Cave indicates that fishing practices continued after the end of the

Mesolithic (Connock, 1985, Connock et al, 1991). The stable isotope evidence from human bone collagen, on the other hand, shows a lack of marine sources in the diet after the onset of the Neolithic (Schulting and Richards, 2002). This is the fundamental issue which this thesis contributes to: the reconciliation and explanation of this conflicting data.

The origin of the argument that there was a sharp shift in diet away from marine resources were $\delta^{13}C$ measurements of Mesolithic and Neolithic humans from Greenland and Denmark (Tauber, 1981) (see chapter 3.2.1 for an explanation of the applications of $\delta^{13}C$ to reconstructing diet). This study showed that despite the coastal setting for both the Mesolithic and the Neolithic populations, $\delta^{13}C$ values reflected a diet dominated by marine resources in the Mesolithic, and a diet completely absent of the same foods in the Neolithic (Tauber, 1981). Bonsall et al. (2002a) later showed that this pattern corresponded with stable isotope values from Scottish Mesolithic and Neolithic human bone collagen. The west of Scotland became of particular interest to those investigating the Mesolithic-Neolithic transition because of its 'marginal environment', which was assumed to have made agriculture difficult to establish, and because of the presence of shell middens that dated to the Neolithic. AMS and stable carbon and nitrogen measurements of human bone from two Mesolithic sites (Cnoc Coig and Caisteal nan Gillean II) were compared with measurements from two Neolithic sites (Carding Mill Bay and Crarae) to estimate that marine consumption fell from 58-100% of the dietary component in Mesolithic, to 0% in the Neolithic (Schulting and Richards, 2002).

The strength of some of these earlier studies could be questioned because of the small sample sizes they utilized, however this same rapid shift away from fishing was also observed when analysing larger populations. This was the case when 164 Neolithic and 19 Mesolithic human bone collagen $\delta^{13}C$ values from Britain were compared and shown to reflect the rejection of fish in the Neolithic (Richards et al., 2003), therefore the data from isotope values from bone collagen in Scotland is consistent and convincing. In later studies, questions about sample sizes from Milner et al. (2004) were dismissed because, without exception, all Mesolithic bones sampled for isotope analysis from all sites in Britain showed high marine consumption, while all Neolithic bone showed a lack of marine resources in the diet (Hedges, 2004). The unambiguous nature of the results from different stable isotope studies strengthens the argument for a sharp shift in diet during the Mesolithic-Neolithic transition.

Like the stable isotope evidence, questions have also been raised about the strength of the archaeozoological evidence of dietary change. Richards and Schulting (2006) argue that too much emphasis has been placed on Neolithic shell middens and that their presence could be due to other factors such as natural accumulation or the use of shells for site drainage. Fish remains within the middens could have been brought in by predators such as otters, and do not prove that fish were exploited by humans (Richards and Schulting, 2006). These arguments are less robust, and could be perceived and contradictory. Domestic animal remains are used to suggest that terrestrial herbivores are the dominant dietary resource in the Neolithic (Richards and Schulting, 2006). if this is the case, then the remains of shellfish and fish must be considered in the same way. It is unreasonable that middens which contain many tonnes of shellfish remains, many dominated by a single species such as limpet or oyster, could have naturally accumulated, or that they were constructed as a building resource only, with the nutritional element of the shellfish ignored or discarded. It is perfectly plausible; however, that a small amount of marine resources could have been included in the Neolithic diet and be undetectable in stable carbon and nitrogen isotope analysis of human bone collagen (see Chapter 3 for further details on detecting marine resources using isotopes).

In an attempt to reconcile the archaeological evidence and the stable isotope evidence, the Neolithic began to be reconsidered (Richards and Hedges, 1999a, Schulting, 2000). Thomas (2003) reasoned that the changes in the regular consumption of fish must have been a conscious choice, or a 'taboo'. He also argued that for the stable isotope data to fit with the archaeological story, we must reject the notion of a swift and homogenous Neolithic in favour of a more gradual and diverse transition (Thomas, 2003). It is unclear if this more gradual transition included a more gradual change in the diet, since Thomas notes that: 'Richards and Hedges have clearly demonstrated that coastal communities in southern Britain stopped eating marine foods at the start of the Neolithic' (Thomas, 2003). Richards and Schulting (2006) interpret that Thomas' paper supports their dietary arguments. Thomas is cited in support of a statement about archaeology beginning to recognise the implications of stable isotope results (Richards and Schulting, 2006).

Though the isotopic evidence for a rapid change in diet at the Mesolithic-Neolithic transition is clear, there are few other methods which back up its claims. Stable isotope analysis is one of the most commonly used and valuable methods of recreating diet; however, analysis of bone collagen reconstructs long term dietary habits over the 5-10 years prior to death,

depending on which bone is sampled (Sealy et al, 1995; Richards and Hedges 1999). This means that minor or periodic contributions of marine resources to a dominantly terrestrial diet (and vice versa) are not detectable in the values. We would expect that there would be other sources of evidence to back up the stable isotope results though. While the analysis of lipid biomarkers and stable isotope analysis of pot residue has shown that dairying replaced fishing in the Neolithic, this method of analysis is limited because it only takes into account one method of cooking (Cramp et al., 2014). Meat and fish can be baked in pit ovens, cooked on heated slabs or roasted over a fire, so we can only say that this method shows that dairy products replaced fish in meals cooked in pots. The statistical analysis of archaeozoology from multiple sites across Europe has indicated that Neolithic communities chose sites that were conducive to agricultural activity rather than hunting (Manning et al., 2013). This supports the argument that farming was far more important to Neolithic people than hunting, but doesn't disprove the notion of occasional or opportunistic hunting and fishing.

There is certainly evidence for some continuity of the Mesolithic lifestyle in early Neolithic Britain. Analysis of $^{87}Sr/^{86}Sr$, ^{18}O and ^{14}C in human bones from Gloucestershire, England revealed isotopic variations in a single burial population, suggesting some mobility in the early farming lifestyle (Niel, 2015). There is also an argument for the development of some aspects of the Neolithic lifestyle during the Scottish Mesolithic. For example, a study of the charred remains of wild trees and plants at 48 Scottish Mesolithic sites, dating from 4000-8600 cal BC, showed evidence of systematic and targeted exploitation of these resources according to factors such as how efficiently they burn, or how useful they are as a food resource (Bishop, 2009). This evidence of an overlap in the Mesolithic and Neolithic lifestyle, while not directly indicative of the extent of marine resource consumption in the Neolithic, strongly supports a more diverse and gradual transition rather than an immediate and permanent shift.

The presence of marine fish and shellfish remains in early Scottish Neolithic sites is a strong indicator that these resources continued to be exploited beyond the end of the Mesolithic period. This point is even suggested by Schulting (2004), an advocate for the argument for a sharp shift in diet at the transition, when he wrote that the archaeological evidence points towards marine consumption in the early Neolithic, but that fish and shellfish were not a significant dietary contributor (Schulting 2004). Recent refinements in isotope analysis have revealed that this could indeed be the case. Incremental sampling of tooth dentine to measure $\delta^{13}C$ and $\delta^{15}N$ to investigate periodic changes in the diet from childhood to early adulthood

has been applied to Scottish Neolithic individuals from Shetland (Beaumont et al. 2013): the occasional enrichment in both carbon and nitrogen isotopes is indicative of short term consumption of marine produce in these early farmers (Montgomery et al., 2013). A limitation of the dentine analysis method is that there are very few tooth samples available from the Scottish Mesolithic and Neolithic with which to broaden the sample size and confirm this argument. Using bulk bone collagen for stable isotope analysis, while more readily available, are also not necessarily suitable for calculating small amounts of marine contribution to the diet. A lack of faunal data reported alongside human bone measurement and the use of spatially and temporally inadequate marine and terrestrial end-members which are used to calculate relative consumption of marine and terrestrial resources in the diet (Milner et al., 2004). We need to therefore find a more appropriate dietary reconstruction method that can be applied to the material that is available in Scotland.

As well as finding a more effective way to demonstrate dietary habits using isotope analysis, we must also seek to fill gaps that currently exist in the academic literature. The scarcity of human remains from the Scottish Mesolithic-Neolithic transition means that it is imperative that we use the right methods and ask the right questions: the most robust tools must be used to analyse the few samples that exist, and the hypotheses that drive this analysis must take into account the empirical evidence of diet from each individual site. The biggest challenge in investigating the Scottish Mesolithic-Neolithic transition is the relative lack of isotopic measurement of faunal remains associated with human bone (Milner et al, 2004). Isotope dietary baselines are essential for accurate dietary reconstruction (see Chapter 3.2.4 for further details on the importance of baselines); however the remains that are required to build them are scarce – especially from the Mesolithic period (Kitchener et al., 2004). We must therefore strive to measure all suitable archaeological samples, where they are available, and develop solutions to fill the gaps in the baselines where possible.

A further gap in our current knowledge of the Scottish Mesolithic-Neolithic transition is the extent of shellfish consumption in either period. Shell middens often contain many tonnes of shell remains, but traditional isotope studies can only distinguish between marine and terrestrial resources, without the ability to distinguish between species consumed. Firstly, the ability to estimate shellfish and fish consumption would be extremely useful, since the two species are acquired using different subsistence practices: fishing required a larger time and energy expenditure than shellfish collecting, which were easily accessible from the shore using rocks to dislodge species such as limpets. Secondly, and perhaps most significantly,

there is isotopic evidence that shellfish species may have lower $\delta^{13}C$ values than marine fish. Average values of -20‰ have been measured in oyster and mussel protein (Bonsall et al, 2009). These values overlap with typical bone collagen values from terrestrial herbivores; if these are representative of typical shellfish values, shellfish consumption may be masked in the human isotope data. The implications of this are twofold: firstly, if Neolithic people supplemented their diet with shellfish, it would be undetectable using isotope analysis and prior conclusions about Neolithic diet would prove incorrect, and, secondly, if there is marine consumption that has not been detected in humans, the radiocarbon dates of these individuals must also be questioned since appropriate marine reservoir effects will not have been considered in the calibration of the dates (Bonsall et al, 2009). Further investigation into shellfish isotopic values and their implications on the isotope measurements of humans who are likely to have eaten them is important to clarify this current gap in the literature.

2.5 Conclusion

Archaeological and analytical investigation of the Scottish Mesolithic-Neolithic transition has been characterised by debate and disagreement. Even defining the two periods has been difficult, and the fact that the Mesolithic and Neolithic were for many years considered completely separately made investigating the transition from one to the other challenging. Large-scale climate change must be considered when defining the drivers of the Neolithic. A shift to warmer and drier conditions in Scotland may have influenced the onset of the Neolithic: the move from dense elm forest to more open woodland made the Scottish landscape much more favourable for the first farmers. More recently, debates have focussed on how the transition arrived from Europe: was it a movement of people or ideas? Current understanding is somewhere in the middle of these two theories – that immigration certainly brought Neolithic populations and practices, but that indigenous populations were active in adopting new farming technology.

This thesis looks beyond the broad questions about how the transition occurred, and narrows its focus upon addressing questions of dietary change at the onset of the Neolithic. Though it is clear that there was a significant change in diet, from relying heavily on marine resources to subsisting on terrestrial domesticates, the rate of this change is the key issue discussed in this research. We are beginning to understand that marine resources may have still played a part in the early Neolithic; however, a new approach to dietary reconstruction using isotope

analysis is required in order to create a clearer picture. Investigating diet in the Mesolithic-Neolithic transition in Scotland is particularly difficult because of the scarcity of human samples to investigate, and of faunal remains to provide robust baselines. Since it is unlikely that a better method of bone recovery is possible, we must find a way to supplement the sparse baselines to ensure that conclusions drawn from the human bone are both accurate and precise. Finally, in a further effort to create robust dietary reconstructions, it is important to consider how we can represent food groups that are present in the archaeological record, but do not survive in a form that can be utilised in isotope studies.

Chapter 3: Stable isotope analysis and Bayesian modelling for dietary reconstruction and ^{14}C age calibration of human bone collagen

3.1 Introduction

This chapter is concerned with the analytical techniques employed in this research in order to investigate diet in Mesolithic-Neolithic Scotland. The primary method of investigation in this thesis was $\delta^{13}C$ and $\delta^{14}N$ analysis. The principles of stable isotope analysis are first outlined, before the chapter discusses literature surrounding the pretreatment methods involved, the applications of stable isotope analysis and the significance of animal bone collagen measurements in human dietary investigations.

The chronology of the samples in this research were also of significant importance, therefore, the various methods of radiocarbon dating different bone collagen samples are outlined and explained. This section focuses on ensuring the accurate and reliable radiocarbon dating of mixed marine/terrestrial human bone collagen samples and discusses how FRUITS is a valuable tool in achieving good quality radiocarbon dates.

3.2 The fundamental principles of stable isotope analysis for dietary reconstruction

Isotopes are forms of an element which differ in atomic mass: they have the same number of protons but differing amounts of neutrons. Isotopes can be either stable or radioactive and in archaeological dietary reconstruction, stable carbon and nitrogen isotope ratios are commonly utilised. Carbon and nitrogen is taken into the body through the diet and used to build different body tissues. In some tissues, such as blood, there is a relatively quick turnover of dietary isotopes as the tissue replenishes itself. Bone collagen, on the other hand, has a much slower turnover period, and so dietary isotopes are fixed into the tissue for 5-10 or more years, depending on which bone is chosen for sampling (Sealy et al., 1995, Richards and Hedges, 1999b).

3.2.1 The application of $\delta^{13}C$ and $\delta^{15}N$ measurements of human bone collagen to diet

By measuring the isotopic composition of bone collagen using isotope ratio mass spectrometry, we can characterise past long term dietary habits. This is possible because different food sources have different isotope 'signatures'. These signatures are a result of isotope fractionation which is caused by physical and biological processes in living organisms. Animals and plants take in carbon and nitrogen via either their diet or via photosynthesis. Some of this is incorporated into body tissues and some is eliminated as waste, and the organisms preferentially excrete the lighter isotope. The process of fractionation means that if we measure the stable isotope values of tissues from animals and the top of the food-chain and compare them to the values of tissue from animals lower down, a visible difference is observed in the ratio of heavier to lighter isotope; for example, carnivores will have higher $\delta^{13}C$ and $\delta^{15}N$ values that the animals they consume (DeNiro and Epstein, 1978, DeNiro and Epstein, 1981).

In the case of carbon in this research, the ratio of $^{13}C/^{12}C$ is measured to distinguish between a terrestrial and a marine diet (Chisholm et al., 1982). This is possible because there are different sources of carbon in each environment. Marine plants photosynthesise using carbon which is derived from oceanic bicarbonate, while terrestrial plants use atmospheric CO_2. Oceanic bicarbonate is enriched in ^{13}C relative to atmospheric CO_2, resulting in a $\delta^{13}C$ difference of c.7-8‰, and this isotopic difference is fixed into the organism during photosynthesis (Smith and Epstein, 1971). The environmental carbon isotope signatures are then passed through the food chain, from source to consumer with a small (c.1‰) offset, so the characteristic environmental carbon source values are reflected in the body tissues of large mammals and humans (Tieszen et al., 1983).

In the case of nitrogen, the ratio of $^{15}N/^{14}N$ is measured to establish the source of dietary protein. The bone collagen of humans and fauna is enriched in ^{15}N relative to the diet; the value of this shift has been the subject of debate in archaeological and ecological sciences. The trophic level shift (Δ_{tro}) was initially posited as being 4.8‰ as calculated from values measured between predator and prey bone collagen from East Africa (Ambrose and DeNiro, 1986). This value was later recalculated by Schwarcz (1991), who noted that there was a large range of values that were recorded from previous studies (Schoeninger and DeNiro, 1984, Schoeninger, 1985). Using a more constrained population of wolves and coyotes

(predators) and deer (prey), Schwarcz defined dietary Δ_{tro} for $\delta^{15}N$ as 2.8‰. This discrepancy in calculated values was resolved by Bocherens and Drucker (2003), who advocated the application of a range value of Δ_{tro} for $\delta^{15}N$ = 3-5‰, following a review of Ambrose and DeNiro's and Schwarcz's data in conjunction with an ecological study of modern carnivores. This range was the accepted value for many years and was routinely applied to bone collagen isotope values of humans and animals to estimate the human dietary protein source.

More recently, the true constrained value of trophic level shift in nitrogen isotopes for human dietary reconstruction is understood to be much closer to Ambrose and DeNiro's original calculation. O'Connell et al. (2012) conducted a feeding experiment using human participants. By measuring the isotopic offset between diet and red blood cells, and by taking into account other offset values in the literature, it was suggested that Δ_{tro} for $\delta^{15}N$ is ~6‰. While the study can be criticised for employing self-reporting methods of data collection, casting some scepticism on the accuracy of the food diaries used to characterise participants' diet, it is the only study so far that uses 'known' isotope values for human diet when comparing against human tissue, meaning that the estimated Δ_{tro} is more likely to be a true representation of human values. Ambrose and DeNiro (1986) and O'Connell et al. (2012)'s estimations of a Δ_{tro} for $\delta^{15}N$ of ~5-6‰ is supported by Fernandes et al. (2015), who reviewed the literature regarding measured shifts between human diet and human hair (Minagawa et al., 1986, Schoeller et al., 1986, Minagawa, 1992, Yoshinaga et al., 1996, Hedges et al., 2009, Huelsemann et al., 2009) and human hair and human bone ((O'Connell and Hedges, 1999, O'Connell et al., 2001, Richards, 2001, Lehn et al., 2015) and reported a diet to bone collagen Δ_{tro} value of 5.5±0.5‰. Since this is the most comprehensively considered and up to date value of Δ_{tro} for $\delta^{15}N$ isotopes in humans, this is the figure that will be employed in the calculation of human diet in this thesis.

3.2.2 Preparing bone collagen and flesh samples for stable isotope analysis

In order to use stable carbon and nitrogen isotope analysis of bone collagen to recreate human diet, the sample collagen must be isolated from the bone. The method for extraction is the same for the pretreatment of radiocarbon dated bone, but there is variation between laboratories as to the protocol followed. Most laboratories follow a version of the Longin (1971) method which involves the removal of the bone mineral portion using acid and then

gelatinization of the 'collagen' in heated water. The variable steps include the addition of ultra-filtering after gelatinization, or an alkali rinse during collagen isolation. Pretreatment using an acid-base-acid protocol developed by Berger and Libby (1966) is still used at some laboratories. Samples are rinsed in NaOH in-between HCl rinsing steps as a means of removing humic contaminants and lipids, but the effectiveness of the alkali step has been questioned and is subsequently not included in SUERC's protocol (Arslanov and Svezhentsev, 1993, Liden et al., 1995, Jørkov et al., 2007, Dunbar et al., 2016).

The pretreatment method at SUERC follows a revised Longin (1971) method and, where requested, will add the extra ultrafiltration step proposed by Brown et al. (1988). Ultrafiltration is sometimes employed as a method of separating degraded collagen, lipids and other contaminants from the sample. Research that compares the two methods (with and without ultrafiltration) has found that there is no difference larger than the accepted measurement variation (1‰) for $\delta^{13}C$ measurements and no significant difference in $\delta^{15}N$ measurements (Jørkov et al., 2007). Protocols should therefore be chosen based on the likely preservation and contamination of the sample. Of course, this is very difficult to determine macroscopically in bone samples, therefore suitable quality control indicators must be employed for every sample. Those with C/N ratios outside of the range 2.9-3.6 (the range of C/N of fresh bone) are indicative of well-preserved collagen (DeNiro, 1985). This range has been refined by Van Klinken (1999) who stated that the accepted range employed at Oxford radiocarbon laboratory is 3.1-3.5. In addition, Van Klinken (1999) recommended that collagen yield be measured to ensure that it is >0.5% of the total sample weight which indicates the sample is unlikely to be contaminated. Adoption of quality indicators such as these mitigates the potential effect of there being several different pretreatment protocols to consider. Ultimately, the choice of protocol among those described above is inconsequential as long as the prepared sample passes these tests.

When measuring stable isotope values of modern bone collagen and modern flesh, the lipids must be removed from the sample. This is because lipids are enriched in ^{12}C compared to bone collagen and flesh. In this research, we are only concerned with the measurement of protein values from flesh and bone; this is following the assumption that dietary protein is routed to tissue protein. The application of ultrafilters or NaOH treatment have proved ineffective in removing lipids, so to achieve an accurate measurement of collagen and flesh values, solvent extraction is commonly applied (Guiry et al., 2016, Liden et al., 1995). Like the practice of collagen extraction, there are a variety of pretreatment protocols used to

remove lipids; however, there are many different variations and no one is favoured over another.

Many lipid extraction methods employ various volumes and ratios of chloroform ($CHCl_3$) and methanol (MeOH), under the assumption that a polar and a non-polar solvent will produce the best total lipid extraction effect (Folch et al., 1957, Bligh and Dyer, 1959, Lee et al., 1996). This is despite research in food chemistry which found that dichloromethane (CH_2CI_2) was more effective than chloroform in removing lipids from fish muscle (Cequier-Sánchez et al., 2008). There is very little consensus over which method is most effective, or indeed, whether precise ratios are required. Furthermore, there is disparity over whether solvent lipid extraction has an unpredictable effect on $\delta^{15}N$ values, necessitating the need to measure two sample aliquots – one extracted and one non-extracted (Sotiropoulos et al., 2004, Guiry et al., 2016). Ferraz et al. (2004) argued that alternatives to solvent extraction should be sought, since solvents were found to extract some protein along with the lipids, although this was demonstrated in tests on human serum, so the effect on bone is unknown. The lack of a standard lipid extraction method in the ecological literature means that it is difficult to judge which would be the best to apply to archaeological research.

Most methods of lipid extraction are rooted in ecological studies. These methods concentrate mostly on animal soft tissue, whereas the research presented here required a method which would be effective for animal soft tissue and bone. There is a paucity of research in archaeology which includes the lipid extraction of bone, with some exceptions. Evershed et al. (1995) used a 2:1 v/v chloroform:methanol solvent system with ultrasonication to remove lipids in modern and ancient bone samples. However, the aim of the study was to investigate the viability of measuring ancient lipids using GC/MS, so the methods cannot be confidently applied to this research. Howland et al. (2003) used an alternative solvent system (10:5:4 v/v methanol/chloroform/water) with ultrasonication on modern pig bone collagen to investigate dietary isotope signals. Unfortunately, the focus of the research was on the viability of fatty and amino acids as opposed to collagen, so the methods are not transferable to this research.

The lipid extraction of modern bone collagen samples in archaeological dietary isotope research is rare. Where lipid extraction has been employed it is not always readily apparent in the publications, such as in the analysis of modern deer bone collagen isotope values following 2:1 v/v chloroform:methanol extraction to investigate the canopy effect (Stevens et al., 2006). While the quality of this research is not questioned, the pretreatment methods

are only very briefly described as following the method after O'Connell et al. (2001), with no reference to whether lipid extraction was warranted or used (Stevens et al., 2006). Since lipid extraction of bone collagen is not a standard practice in archaeology, it would have been helpful if the method in this case had been more thoroughly addressed. It can also be argued that, given the lack of a standard lipid extraction method of bone collagen in either ecology or archaeology, that more work is required to establish a consensus protocol.

3.2.3 The strengths and limitations of stable isotope analysis for dietary reconstruction

As with any other analytical tool, there are strengths and weaknesses that must be weighed up when considering stable isotope analysis for dietary reconstruction. The technique is both reliable and adaptable, having been established over thirty years ago and now being amongst the most popular methods of exploring palaeo-diet globally and across time periods (Richards et al., 1998, Müldner and Richards, 2005, Gregoricka and Judd, 2016). There are also huge advantages in being able to measure dietary isotopes in different body tissues to examine dietary changes over an individual's lifetime. Stable isotopes are fixed in enamel and dentine while the teeth are formed, allowing an investigation of childhood diet while analysing bone collagen gives a view of diet in the years before death (Wright and Schwarcz, 1999). Recent developments in stable isotope techniques have allowed for the analysis of compound specific amino acids in ancient bone and hair samples (Macko et al., 1999). These analyses can give more detailed information on protein sources than can be garnered via the analysis of bulk bone collagen (Corr et al., 2005, Webb et al., 2015), and the ability to analyse hair allows investigation of diet in the days and weeks before death (Wilson et al., 2007). Since stable carbon and nitrogen isotope analysis has these many different applications, it has proven a useful technique in multiple disciplines. This means that there are academics across archaeology, ecology, zoology and forensics that are using and further developing stable isotope analysis.

As well as being able to analyse multiple body tissues, there is significant value in being able to reconstruct diet directly from the remains of individuals. Faunal remains and the chemical analysis of food residue on potsherds are helpful in characterising diet, but can only inform on the group diet and the timeline for these reconstructions can be ambiguous. It can be difficult to determine the length of time that a midden or cooking pot was in use,

and similarly, how many were using each resource. A disadvantage of bone collagen analysis, though, is that it is only usually capable of supporting very broad interpretations of diet. This is not beneficial for the study of periods such as the Mesolithic-Neolithic transition where we suspect that changes in diet may have been much more subtle and geographically variable. The debate regarding the change from a marine based diet to a terrestrial one (see chapter 2.4) has been hampered by the fact that traditional methods of using stable isotope analysis will not detect small contributions (c.<20%) of marine foods in a predominantly terrestrial diet and vice versa (Ascough et al, 2012). Bone collagen can only give us information on the sources of dietary protein, which may be misleading in a high carbohydrate/low protein diet. We need to develop a way of expanding the limits of precision for stable isotope analysis of diet.

Another pressing concern regarding stable isotope analysis for dietary reconstruction, which was also the primary reason for this research, is that the technique relies on a baseline which is not always available. Baselines are constructed from the faunal remains found on site, but do not consider foods that may have been lost to degradation. Very few stable isotope studies take into account all available food sources when reconstructing diet because of the limited availability of samples to measure. Other studies use non-local faunal remains in an attempt to fill baseline gaps, but overlook that one of the fundamental reasons for building a baseline is to correct for natural geographical variations in isotope values that are reflected in every stage of the food-chain (Peterson and Fry, 1987). There is a growing awareness in the literature, particularly in work concerned with the British Mesolithic-Neolithic transition, that more research is required to build representative faunal baselines (Charlton et al., 2016) We must begin to address people's use of and relationship with animals, as argued by Hoffman (2015) who highlighted the excessive focus on the nature of migration during the Mesolithic-Neolithic transition. The problem in Scotland is that both human and faunal skeletal remains from Mesolithic and Neolithic sites are scarce. Representative baselines are not possible given the assemblages that exist. This research was primarily concerned with addressing this specific problem by supplementing ancient baselines with modern samples.

3.2.4 The importance of a representative dietary faunal baseline and the limitations of a 'traditional' dietary faunal baseline.

A faunal dietary isotope baseline is usually comprised of stable isotope measurements of animal remains found within the same context as the human samples in a palaeo-dietary study. It controls for natural temporal and geographic variation in isotope ratios, ensuring that only dietary variation is interpreted in human bone collagen values (Richards and Hedges, 2003, Drucker and Bocherens, 2004). Baseline measurements are crucial to understanding human diet; $\delta^{13}C$ values are used to differentiate between a marine and terrestrial diet, and $\delta^{15}N$ indicates trophic level shift between diet and consumer, and dietary assumptions are made based on the isotopic offset between the consumer and their diet (Richards and Hedges, 1999b). A representative baseline is particularly important in Scottish coastal sites, where it has been shown that terrestrial animals that feed on seaweed and are subsequently consumed by humans may distort estimates of marine resources in the diet. This phenomenon is represented in the collagen of ancient fauna as increased $\delta^{13}C$ and $\delta^{15}N$ values, and has been observed in the modern flock of sheep on North Ronaldsay (Balasse et al., 2006). A full and representative isotope baseline is, therefore, essential for accurately recreating human diet in the Scottish Mesolithic-Neolithic transition.

The study of the transition from a nomadic hunter-gatherer-fisher lifestyle to sedentary farming in Scotland is greatly hampered by the scarcity of human and animal remains that survive in the archaeological record. Some dietary resources, such as shellfish are well represented, but the edible organic portion has either been consumed or totally degraded, leaving only the inorganic shells. Richards et al. (2001) investigated the viability of using modern analogues in archaeological sulfur stable isotope studies. While only a small sample size was measured (N=7), the modern fauna measurements were distinct from archaeological fauna values, and it was concluded that the difference was a result of pollutant sulfur in the modern samples (Richards et al., 2001). So it seems, for the UK at least, that modern analogues may not suitable for dietary investigations which include sulfur isotopes. While potentially unsuitable for dietary studies, Richards et al observed that sulfur isotopes may be useful for studying increases in pollution over time. This appears to be the same conclusion reached through research on modern and ancient $\delta^{13}C$ and $\delta^{15}N$ isotopes in Australia. Pate et al. (1998) was confident in concluding that modern faunal carbon and nitrogen isotope measurements would be useful in informing on the past climate and ecology of Australia, but were uncertain that these isotopes could be applied to dietary studies. Even if there was

clarity on the matter of modern isotope baselines in Australia, the findings could not be applied to archaeological and modern samples in Scotland since the two are such distinct and distant environments. This warrants investigation into the feasibility of using modern fauna in ancient isotope baselines for Scottish sites as well as the need to use tools that are able to quantify the relative abundance of food groups in past diet.

3.3 The fundamental principles of radiocarbon dating

Radiocarbon dating is used to calculate the calendar age of organic samples such as bone, wood, shell, plants and seeds. This technique is based on the fact that carbon within all living organisms is at isotopic equilibrium with environmental carbon. When the organism dies, carbon exchange with the atmosphere or marine environment ends and ^{14}C in the sample begins to decay at a known rate (T½ = 5730 years). Thus, when the radiocarbon content of an archaeological sample is measured, it is possible to calculate how long ago the radioactive decay process began, and therefore the date at which the organism died.

Cosmic rays hit Earth's upper atmosphere, producing neutrons; these particles then react with ^{14}N to produce ^{14}C. Radiocarbon then reacts with atmospheric oxygen to form CO, which subsequently oxidises to form CO_2. The radiocarbon then disperses as gas throughout the atmosphere and is exchanged as part of the carbon cycle: in the terrestrial environment, CO_2 is passed through the food chain after it is initially absorbed by plants via photosynthesis, in the marine environment, the gas is accessible to organisms after it has dissolved in ocean water. Accelerator mass spectrometry (AMS) radiocarbon dating works by measuring the abundance of the radioactive isotope of carbon (^{14}C) in a sample in comparison to a stable isotope of carbon (usually ^{12}C). Oxalic acid is used as the modern reference standard to represent the carbon isotope ratios of living organisms (A_{ON}) and sample $^{13}C/^{12}C$ ratios are normalised to $\delta^{13}C$ = -25‰ (A_{SN}). The radiocarbon age is then calculated using the following equation: T = -8033 1n$t = -8033\ 1n\ \frac{A_{SN}}{A_{ON}}$ (Struiver and Polach, 1977).

3.3.1 The terrestrial and the marine calibration curve

The abundance of atmospheric radioactive carbon has fluctuated over the millennia, therefore, the terrestrial calibration curve (IntCal13) was developed by Reimer et al (2013) and is periodically refined in order to provide the most accurate calculation of calendar age. The curve is formulated using the measurements of ^{14}C in known age samples. Tree rings dated via dendrochronology form the basis for the calibration curve up to around 12,550 cal BP (Reimer et al., 2013). Beyond this, samples such as plant macro-fossils and uranium-series dated speleothems are utilised to extend the calibration curve to around 50,000 BC (Reimer et al., 2013). Accurately dating samples from the 20th and 21st centuries is problematic, since the burning of fossil fuels and the testing of nuclear weapons in the mid-20th century drastically altered the atmospheric abundance of ^{14}C; however, research has shown potential for the development of a calibration curve for post bomb peak samples (Goslar et al., 2005, Wild et al., 2000).

Radiocarbon dating marine samples requires the utilisation of a marine calibration curve (Marine13), as opposed to the terrestrial curve. The reason for this is that carbon is stored and cycled for much longer periods in the marine environment. Carbon taken in by marine organisms is much older than atmospheric carbon, therefore, archaeological marine samples generally produce a radiocarbon age that is older than the true sample date. This age offset is an average of approximately 405 years (Hughen et al., 2004), but the offset values for individual samples vary by location around the globe. The marine calibration curve is generated by modelling the ocean response to atmospheric ^{14}C variations based on the tree-ring data used to generate IntCal13 back to 12,550 cal BP. This accounts for the attenuation of atmospheric ^{14}C fluctuations observed in the atmosphere, because the oceanic response to these fluctuations is slow. Beyond the limit of the tree ring data, the curve is generated from the corals. The marine calibration curve is applied to calibrated marine ^{14}C dated samples to the globally modelled average offset and the application of local marine offset values (ΔR yrs) is necessary to calculate the calendar date of an archaeological marine sample (Reimer et al., 2013).

3.3.2 Calculating local marine reservoir offsets (MREs)

Local MREs (marine reservoir effects) vary over time and between global locations; a ΔR value for any given site is defined as the difference in radiocarbon age between the global average reservoir age and a local marine sample at a single point in time (Stuiver et al., 1986). To find a ΔR value, it is necessary to find the terrestrial ^{14}C age that corresponds to the measured marine age. This can be determined using known age samples, tephra isochrones and paired marine terrestrial samples (Ascough et al., 2005). Although ΔR can be determined by comparing just one pair of contemporary and local samples, this research employed the multiple paired marine/terrestrial samples approach, which reduces the risk of producing potentially misleading values from single pairs; this is achieved by considering 16 possible ΔR values from eight samples (four terrestrial and four marine) (Ascough et al., 2009, Russell et al., 2015). This improved value is calculated as follows: a ΔR value is calculated for all possible pairs and outliers in the data are then excluded using a χ^2 test. A weighted mean of each paired offset is then calculated, with the variability expressed as the standard error for predicted values (Cook et al., 2015). This method was developed relatively recently; however, research is ongoing to further improve the calculation of ΔR values (Reimer and Reimer, 2016).

Scotland's ΔR record is extensive and, as a result, precise ΔR values for the west coast of Scotland, the east coast of Scotland, the Orkney islands and a mean value for all Scottish sites have been produced for the Neolithic period through to the Medieval period (3500 BC to 1450 AD) (Reimer et al., 2002, Ascough et al., 2007, Ascough et al., 2009, Russell et al., 2015). Despite rich MRE and ΔR data for Scotland, radiocarbon dating human remains from the Scottish Neolithic, complications arise due to the fact that the samples usually contain a mix of both marine and terrestrial carbon derived from the diet. Samples such as these must be calculated differently from those that contain either 100% terrestrial carbon or 100% marine carbon. Approaches to radiocarbon dating these mixed samples are considered below.

3.3.3 Radiocarbon dating mixed marine/terrestrial bone collagen

In order to accurately radiocarbon date samples which contain both marine and terrestrially derived carbon, it is necessary to quantify the abundance of marine carbon in the material to

be measured. Mixed marine/terrestrial samples are almost always samples of human or fauna bone collagen. These samples could be either omnivorous fauna (e.g. pigs or foxes) (Ascough et al., 2012), or seaweed-eating herbivores (e.g. sheep) (Balasse and Tresset, 2009). Since the carbon in bone collagen is derived from the diet, it is important to understand the sources of dietary protein for the individual human/animal. This is commonly achieved via stable isotope analysis, but there are several methods of using the isotope data to calculate the relative abundance of marine and terrestrial dietary protein in bone collagen. (See section 3.4 for a review and comparison of these methods).

Once dietary information has been determined, this data must be applied to generate a radiocarbon date in Oxcal, the radiocarbon calibration programme utilised across the field of archaeology which was developed by the Oxford Radiocarbon Accelerator Unit. The data required for the calibration are the radiocarbon age BP, the estimation of the abundance of marine protein in the diet and the appropriate ΔR value for the site. All of these data must be presented with an associated error where possible before they are calibrated using the mixed curve in Oxcal. There are a greater number of variables involved in calibrating a mixed marine/terrestrial sample than for a terrestrial sample (where only the radiocarbon age BP is required), making the calibration of such mixed samples much more complex. The dietary estimates for each mixed sample must therefore be carefully considered in each instance using the best modelling technique available. Linear regression is commonly applied, but was deemed unsuitable for this research, the reasons for which are outlined below. Instead, the Bayesian mixing model FRUITS was utilised to model the diverse diet for each Neolithic human in this research.

3.4. The application of FRUITS in this research

In order to overcome the issues related to traditional methods of interpreting dietary isotope measurements (these issues are considered in section 3.4.2), as well as the issues related to the use of unrepresentative faunal baselines (see section 3.2.5), a mathematical modelling approach was used.

3.4.1 Using FRUITS to accurately reconstruct palaeodiet

The model used throughout this work was FRUITS (Food Reconstruction Using Isotopic Transferred Signal). Fernandes et al. (2014), the creator of FRUITS, defined the model as follows:

$$H_k = \frac{\sum_j \left(W_{jk} \sum_i \alpha_i C_{ij} \left(I_{ijk} + T_k \right) \right)}{\sum_j \left(W_{jk} \sum_i \alpha_i C_{ij} \right)}$$

Where:

H_k = *k*-th dietary proxy in the consumer, modelled as a normal distribution, $H_k \sim N(\mu_{H,k}, \sigma^2_{H,k})$ with $\mu_{H,k}$ = average value and $\sigma^2_{H,k}$ = associated variance.

α_i = unknown dietary proportion of *i*-th food group. Here $0 \leq \alpha_i \leq 1$ for $i = 1,\ldots,n$ and $\sum_{i=1}^{n} \alpha_i = 1$ where n = number of food groups.

I_{ijk} = isotopic signal from the *i*-th food group, the *j*-th food fraction, and associated with the *k*-th dietary proxy. Assumed to be a random variable, modelled as a normal distribution $I_{ijk} \sim N(\mu_{I,k}, \sigma^2_{H,k})$.

T_k = diet-tissue offset for the *k*-th dietary proxy, modelled as a normal variable $T_k \sim N(\mu_{T,k}, \sigma^2_{T,k})$.

W_{jk} = weight contribution of the *j*-th food fraction in forming the *k*-th target signal, modelled as a normal variable $W_{jk} \sim N(\mu_{W,jk}, \sigma^2_{TW,jk})$.

C_{ij} = concentration of the *j*-th fraction of the *i*-th food group, modelled as a normal variable $C_{ij} \sim N\ (\mu_{C,\,ij}, \sigma^2_{C,\,ij})$.

FRUITS runs using BUGS (Bayesian inference Using Gibbs Sampling) and provides estimations of α_i (user defined contributions of food groups to diet) using Markov chain Monte Carlo (MCMC) calculations. Data is reported as a text report with an associated BUGS script, and as box and whisker plots showing the mean and median value with 68% and 95% credible intervals, and probability distributions. Repeated testing using data from human and animal bone collagen stable isotope values has shown FRUITS to be highly accurate in predicting relative dietary compositions (Fernandes et al., 2014, Fernandes et al., 2015, Sayle et al., 2016).

There are several advantages of using FRUITS in comparison to using other dietary modelling techniques such as linear regression or IsoSource. Linear regression modelling is only appropriate for modelling rather simple diets, e.g. marine vs. terrestrial, FRUITS, on the other hand, is capable of solving for multiple food groups simultaneously. This is an essential requirement in this research where potentially small changes in complex diets are being investigated during a time of change in subsistence practices. In addition to this, the probability distributions based on Bayesian statistics which are the output of FRUITS contain far more information than the fixed errors associated with linear regression, or the output of an IsoSource model which does not take into account the isotopic errors associated with food group values (Fernandes et al., 2014).

The more complex and detailed output of FRUITS models enables a more informative interpretation of dietary habits. In addition, FRUITS provides a user friendly and easily accessible interface in which to enter data and run the program. This is in contrast to other Bayesian techniques such as MIX-SIAR which requires the user to be competent in the programming language R. For these reasons it was identified as the most appropriate tool to answer questions of resource use in Neolithic Scotland given the sparse nature of sample material available to work with and the specific debates about diet during the Mesolithic-Neolithic transition.

As with all mathematical models, there is a risk of inaccurate data being reported if the input data for FRUITS dietary reconstructions are not properly considered. This would ultimately result in erroneous conclusions being drawn about past diet. To minimise these risks, the work of Phillips et al (2014) on best practice recommendations for using dietary mixing models was considered. Some of the suggestions are somewhat uninformative, since they reflect good scientific practice that should be applied to any and every archaeological investigation, such as the advice to 'use prior knowledge to identify questions and spatial and temporal scales' (Phillips et al., 2014). There are; however, some invaluable guidelines proposed that are very specific to recreating ancient diet using stable isotope analysis and a mixing model. Defining well considered diet-tissue offsets are identified as an essential factor in accurately reconstructing palaeodiet (Phillips et al., 2014). Poorly defined tissue offsets result in inaccurate food value data being input into dietary reconstruction models, and therefore, to poor dietary estimates and data interpretations. Since there is so much uncertainty surrounding diet-tissue offsets, it was determined that the best approach in this research was to measure species and location specific $\Delta^{13}C_{\text{muscle protein-lipid free bone collagen}}$ and $\Delta^{15}N_{\text{muscle protein-lipid free bone collagen}}$ offsets for the faunal samples included in the models. This would give the best baseline measurement (since they are the result of species specific and known values), and therefore the most accurate diet-tissue offset values for human diet.

3.4.2 Using FRUITS to improve the accuracy of radiocarbon dates

Obtaining the best representation of dietary habits in the Scottish Mesolithic and Neolithic is not only important when attempting to detect small variations in diet over the period, there are also implications for radiocarbon dating human bone from this period. In order to reliably determine the age of bone, it is necessary to calculate the proportion of marine resource contribution to the diet. This is so that the amount marine protein carrying a MRE in the sample can be calculated, and a correction factor can be applied to rectify the age offset.

The measurement of % marine resources in a human diet is routinely carried out in order to calculate the marine reservoir effect (MRE) correction factor, and also to investigate dietary differences through time and between populations. Linear interpolation is the simplest and most common model to estimate % marine resource contribution to the diet (Arneborg, et al, 1999). Simple linear interpolation is applied by estimating marine and terrestrial $\delta^{13}C$ end point values, and plotting the isotope values of the consumer onto this line after a 3-5‰

offset for trophic enrichment between the humans and their diet has been applied. Endpoints represent isotope values of human bone collagen where a 0% marine diet and a 100% marine diet has been consumed, and these values can be determined in a variety of ways. $\delta^{13}C$ endpoints are usually defined using previously published values; these are typically -12.5‰ for a 100% marine diet, and -21‰ for a 100% terrestrial diet, which are measurements derived from a late Holocene Eskimo population, understood to have subsisted on a 100% marine diet (Grummesgaard-Nielsen, 1997, Lynnerup et al., 1997) and from $\delta^{13}C$ values from four Swedish and Norwegian populations of varying age who are known to have eaten a negligible proportion of marine derived resources (Johansen et al., 1986, Liden et al., 1995). These isotope dietary endpoints were, for example, the values used to calculate the % marine contribution to the diet of the skeleton from Greyfriars, which was subsequently identified as the remains of Richard III (Hamilton and Bronk-Ramsey, 2012).

While the application of linear interpolation using isotope dietary endpoints has the advantage of simplicity, FRUITS has been selected as the preferred method of determining % marine contribution to the diet for the purpose of calibrating radiocarbon dates using the mixed marine/terrestrial calibration curve. There are several advantages of using FRUITS in comparison to using other dietary modelling techniques such as linear regression or IsoSource. Linear regression modelling is only appropriate for modelling rather simple diets, e.g. marine vs. terrestrial, FRUITS, on the other hand, is capable of solving for multiple food groups simultaneously. This is an essential requirement in this research where potentially small changes in complex diets are being investigated during a time of change in subsistence practices. In addition to this, the probability distributions based on Bayesian statistics which are the output of FRUITS contain far more information than the fixed errors associated with linear regression, or the output of an IsoSource model which does not take into account the isotopic errors associated with food group values (Fernandes et al., 2014). The more complex and detailed output of FRUITS models enables a more informative interpretation of dietary habits. For these reasons it was identified as the most appropriate tool to answer questions of resource use in Neolithic Scotland given the sparse nature of sample material available to work with and the specific debates about diet during the Mesolithic-Neolithic transition.

3.4 Conclusion

Work is required in several areas of research related to ancient dietary reconstruction, and particularly to reconstructing the diet in Mesolithic and Neolithic Scotland. A standard method of extracting lipids from modern and ancient bone and modern muscle tissue is required to ensure that a) the most effective and the most appropriate method is always chosen, and b) that isotope data that is produced from lipid extracted tissue at different laboratories is comparable. Because of the specific issues related to sample availability, from Scottish Mesolithic and Neolithic sites, work is required to ensure that dietary isotope baselines are representative in terms of both sample size and food groups. A method to improve the precision of dietary estimates resulting from stable isotope analysis is also required as the technique is not currently able to be used to answers questions about diet where there may be small contributions of marine resources or where the diet being investigated is complex. Finally, since FRUITS is a relatively new model, its boundaries and capabilities must be tested to decide how suitable and adaptable it is to answering different questions about ancient diet.

Chapter 4: Materials and Methods

4.1 Introduction

This chapter describes the samples used in this research and the pre-treatment, analytical measurement, and data analysis methods employed to produce results. Details regarding the criteria used for selecting archaeological sites are followed by a summary of each site to place the samples in context. Several different protocols were used to pre-treat modern and archaeological bone, modern flesh and archaeological shell for analysis of light stable isotopes ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) by isotope ratio mass spectrometry and radiocarbon (^{14}C) age measurement by accelerator mass spectrometry (AMS). Modern and ancient stable isotope results from human and faunal bone collagen were subject to statistical testing using SPSS and modelling using FRUITS version 2.1.1 (Fernandes et al., 2014) in order to quantify different dietary components. Modern stable isotope results from faunal flesh, bone collagen, lipid extracted flesh and lipid extracted bone collagen were used to calculate tissue offsets for the FRUITS models. ^{14}C data were calibrated using OxCal 4.2 (Bronk Ramsey, 2009) and the either the marine, terrestrial or mixed marine/terrestrial calibration curves to calculate the calendar age range of the sample (Reimer et al., 2013). Samples utilised for the production of ΔR values were analysed using a multiple paired samples approach (Ascough et al., 2009, Russell et al., 2015) and a χ^2 test (Ward and Wilson, 1978) to calculate the ΔR value.

4.2 Summary of Archaeological Sites

Archaeological sites for this research were chosen to reflect a wide geographical area so that any potential spatial variation in stable $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ measurements could be investigated. Sample availability and site chronology were considered when choosing sites; it was important that faunal and/or human skeletal remains were available for sampling and that the collections were dated by either typology or radiocarbon dating to the Scottish Mesolithic (10,000 to 3800 BC approx.) or Neolithic periods (4000 to 2000 BC approx.). Historic Environment Scotland's Canmore database (https://canmore.org.uk/), a periodically updated online national record of archaeological sites in Scotland, was utilised in the search for sites. It was originally intended that this research would cover a large range of sites across the whole of Scotland, and the sample population would have therefore benefitted from some

inland, freshwater or east coast sites, but the very nature of the project prevented the acquisition of such samples: Mesolithic and Neolithic human and faunal bone assemblages are extremely rare in Scotland, and is the primary reason for the necessity of this research. This thesis addresses the problem of accurate dietary reconstruction with limited human and faunal samples.

Due to the availability of archaeological samples, sites were mostly limited to the coast and islands: five sites were located on the west coast of mainland Scotland around and off the coast of Oban, two sites were elsewhere on the mainland and three sites were on the Orkney Islands (see table 4.1 for grid references). It was important to choose sites dated to the Mesolithic and the Neolithic, with a focus on sites dated to the transition between the two (4000 – 3600 BC), since this research was designed to investigate changes in diet and subsistence across the two archaeological periods. A good chronological range was achieved, with sites dating from 6400 BC to 2700 BC, and the majority of sites dating to the Mesolithic-Neolithic transition and the early Neolithic.

Figure 4.1 Geographical location of all archaeological study sites throughout Scotland. Legend codes are detailed in table 4.1.

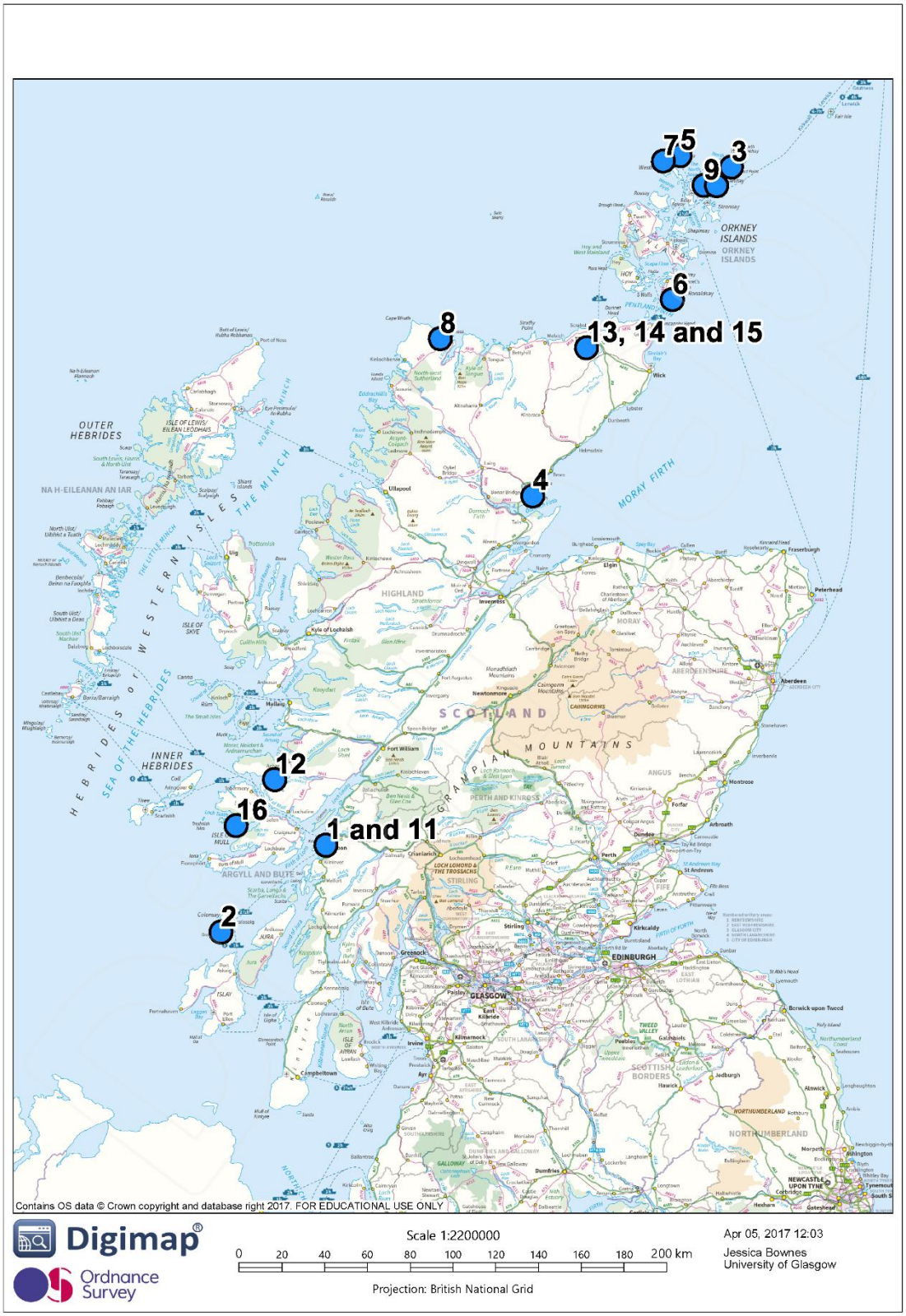
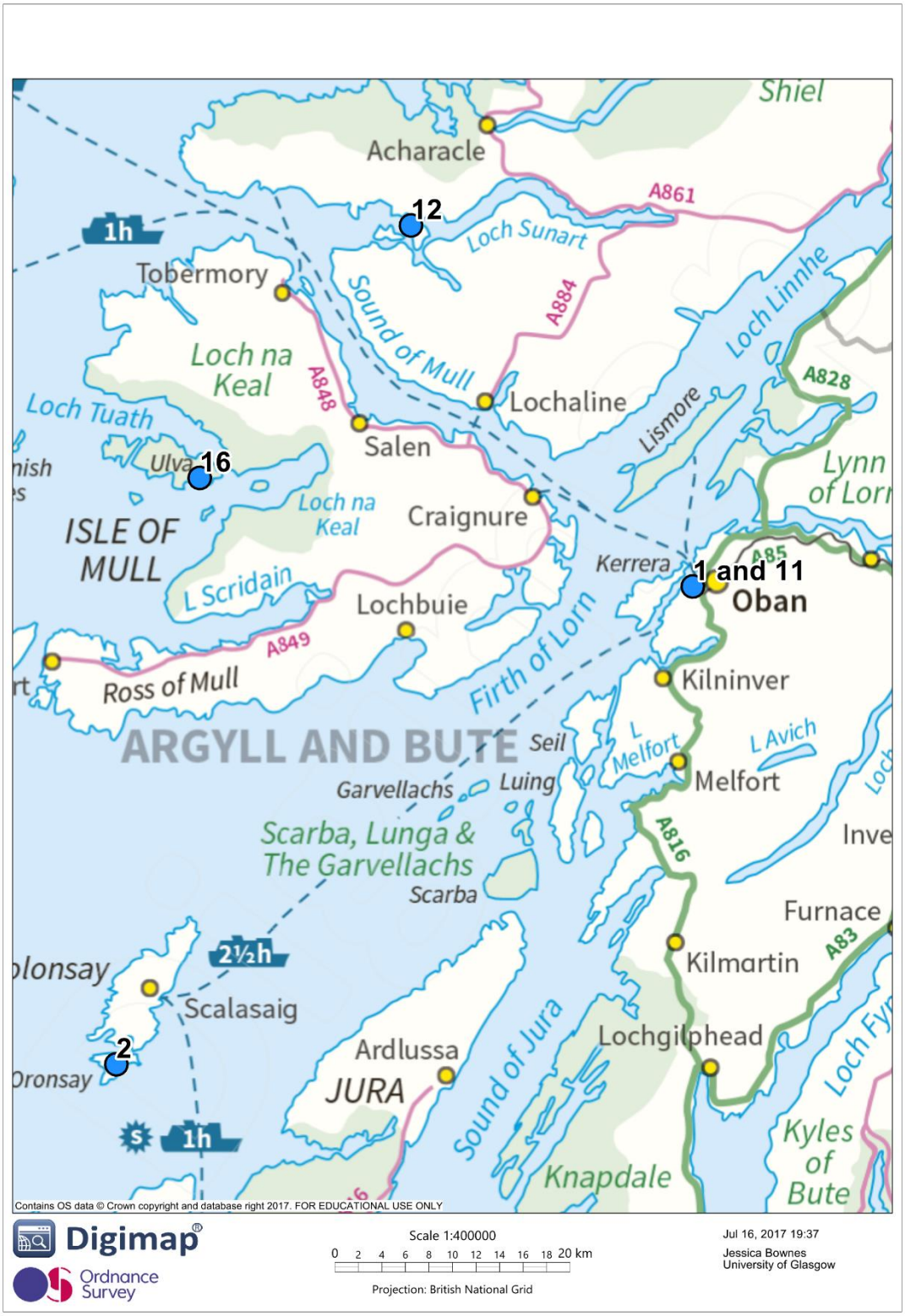


Table 4.1 Summary information for all archaeological sites shown in figure 4.1 in alphabetical order

Site Code	Figure 4.1 Legend	Site Name	Geographical Location	UK National Grid Reference
CMB	1	Carding Mill Bay	Oban	NM 847 294
CC	2	Cnoc Coig	Oronsay	NR 3605 8857
CT	3	Crow Taing	Sanday	HY 74676 46429
EB	4	Embo	Dornoch	NH 8177 9265
HPW	5	Holm of Papa Westray	Papa Westray	HY 5070 5185
LoN	7	Links of Noltland	Westray	HY 428 493
LB	8	Loch Borralie Cave	Durness	NC 3855 6622
PL	9	Pool Bay	Sanday	HY 619 379
QN	10	Quoyness	Sanday	HY 6766 3779
RC	11	Raschoille Cave	Oban	NM 8546 2888
RG	12	Risga	Loch Sunart	NM 611 599
TtS	13	Tulach an t'Sionnach	Loch Calder	ND 0704 6192
TAA	14	Tulloch of Assery A	Loch Calder	ND 0682 6188
TAB	15	Tulloch of Assery B	Loch Calder	ND 0676 6186
UC	16	Ulva Cave	Ulva	NM 4314 3843

4.2.1 Sites located on the west coast of Scotland

Figure 4.2 The locations of Risga (12), Ulva (16,) Carding Mill Bay and Raschoille Cave (1 and 11) and Cnoc Coig (2) on the west coast of Scotland



Carding Mill Bay, Oban

Carding Mill Bay is a Neolithic shell midden on the west coast of Scotland (Figures 4.1 and 4.2) comprising a variety of faunal and some human remains within an abundance of accumulated shell, mostly limpet (*Patella vulgata*). Radiocarbon dating places Carding Mill Bay within 4230 to 2700 cal. BC (Connock et al., 1991, Bronk Ramsey et al., 2000). The midden was excavated by Lorn Archaeological Society and finds analysis carried out by Historic Environment Scotland. Finds included animal bone and antler, human bone in discrete burials and a range of Obanian lithics (Connock et al., 1991). There were disarticulated human remains in several contexts of the midden (IV, VII, X, XIV, XV and XXIII) and a cist burial in contexts II and III (Connock et al., 1991). Carding Mill Bay has been the subject of several published studies investigating the Scottish Neolithic because of its rich skeletal and cultural assemblages (Schulting and Richards, 2002, Bishop et al., 2009, Bartosiewicz et al., 2010).

Studied samples included in this thesis were provided by Glasgow Museums Research Centre and comprised of 16 samples. Species sampled included red deer *(Cervus elaphus)*, large mammals that included cattle (*Bos taurus)* and/or red deer and medium mammals that included sheep (*Ovis aries)*, and/or roe deer *(Capreolus capreolus*), to form the isotope faunal baseline for the site. Contexts which had associated human remains were targeted, but samples were taken over a variety of stratigraphic layers above and below the early shell midden, which has a radiocarbon age of 5060 ± 50 ^{14}C yrs BP (GU2796) (Connock et al., 1991) (3965-3714 cal BC), to determine potential changes in isotope ratios over time. Published stable isotope values of four human individuals from the work of Schulting and Richards (2002) were modelled in FRUITS along with the new stable isotope baseline measurements to create dietary reconstructions. Eight further cattle bone (*Bos taurus*) samples and eight limpet (*Patella vulgata*) shells from the midden were obtained for the purpose of calculating a temporally and geographically appropriate ΔR value for the site (ΔR is the local offset from the global average surface water marine reservoir effect).

Cnoc Coig, Oronsay

Cnoc Coig is located on the Inner Hebridean island of Oronsay (figures 4.1 and 4.2) and was initially excavated in the late 19th and early 20th centuries. It is one of a series of Mesolithic

shell middens that are unique in Scotland in that, to date, they contain the only excavated human remains that survive from the period. There is an abundance of middens on Oronsay made up predominantly of limpet (*Patella vulgata*) shell, but including cockle (*Cardium edule*), whelk (*Nucella lapillus*), periwinkle (*Littorina littorea*), oyster (*Ostrea edule*), scallop (*Pecten maximus*) and razor shell (*Ensis sp.*) which are common to Mesolithic and Neolithic sites (Mellars and Payne, 1971). While bird and crustacean remains were also present, the remains of terrestrial mammals were not reported in abundance. Other finds include stone and antler tools, flint microliths and worked pebbles (Mellars and Payne, 1971). Cnoc Coig and its surrounding middens have been the subject of debate in a variety of publications, owing to the uncertainty of chronology and subsistence practices there, as well as its status as one of the rare Mesolithic sites with associated human bone that survives in Scotland. While stable isotope evidence revealed a year-round exploitation of marine resources, the small size of the middens and the material culture represented on the site do not support this hypothesis, and this remains an unresolved issue (Richards and Mellars, 1998, Richards and Sheridan, 2000, Mithen, 2000, Bonsall et al., 2002a, Meiklejohn et al., 2005).

The data for the human population from Cnoc Coig within this thesis are made up of both new and previously published values. Three human bone collagen stable isotope measurements by Schulting and Richards (2002) were supplemented by new measurements on an individual sourced from National Museums Scotland. No faunal remains were available for sampling from the site, and so values published alongside the humans were supplemented with values from equivalent modern red deer, limpet, winkle, cockle, cod, haddock and pollock samples where these analogues were found to be appropriate.

Raschoille Cave, Oban

The Scottish Development Department (Ancient Monuments) ordered a rescue excavation of Raschoille cave (see figures 4.1 and 4.2) after its discovery in 1984 (Connock, 1984). Lorn Archaeological and Historical Society recorded finds in the form of a substantial amount (approximately 17 kg) of bone belonging to both humans and other fauna, along with approximately 11 kg of marine shells of varying species (Connock, 1985). A relative lack of material culture and other signs of long term settlement were noted in the same report: only one arrowhead and two small charcoal deposits were recorded (Connock, 1985).

Radiocarbon ages for animal bone, human bone, charcoal, hazel nut shell and marine shellfish shell, recorded on the Canmore database, show that the site had a long chronology. The earliest remains comprised a red deer bone dating from the Mesolithic (OxA-8396 7640 ± 80 BP), while the latest were human remains dating to the Neolithic (OxA-8537 4535 ± 50 BP) (https://canmore.org.uk/c14index/22924).

Bone samples from nine human individuals from the site were provided by National Museums Scotland for radiocarbon dating and stable isotope analysis. There was no available associated animal material from the site; however, a local and contemporary stable isotope faunal baseline for these samples was constructed from the baseline at Carding Mill Bay, Oban. The ancient baseline was supplemented by a modern local baseline where samples proved to be isotopically comparable.

Risga, Loch Sunart

A large amount of animal bone and stone tools were recovered from the shell midden at Risga, a small island off the west coast of Scotland, in the 1920s. These are now curated at the Glasgow Museums Research Centre. Following an initial survey in 1993, the midden was further excavated and found to contain a large volume of lithics, comprising approximately 5000 pieces of quartz and some flint and bloodstone (Pollard et al., 1994). The size of the stone and bone assemblages is remarkable, given how small the site is (12 ha). Radiocarbon ages recorded on the Canmore database confirm that the site is of Mesolithic age (OxA2023 5207 to 4705 cal BC and OxA3737 4932 to 4550 cal BC; both dates are from red deer antler collagen) (https://canmore.org.uk/c14index/22508).

The samples from Risga represent the isotope faunal baseline for the Mesolithic period in this research. Twelve bone samples were analysed: the sample population comprised of three different species, red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*) and pig (*Sus scrofa*) and were provided for stable isotope analysis by Glasgow Museums Research Centre. These measurements provided a comparison of isotope value differences between Mesolithic and Neolithic faunal bone collagen. They also formed the isotope baseline for the human sample at Cnoc Coig, Oronsay; there were no available samples to form a baseline from Cnoc Coig; however, Risga is a suitable substitute as it is located close by (approx. 1 km away) and both sites date to the Mesolithic.

Ulva Cave, Ulva

The island of Ulva is located off the west coast of Scotland, near to Mull and directly to the west of Oban (figures 4.1 and 4.2). The cave is a single chamber with a midden inside the entrance; this, and the entire cave floor, was found to be rich with marine and terrestrial faunal, and plant remains. The assemblage included species of shellfish, fish, bird, terrestrial and marine mammals, and carbonised seeds and hazelnut shells (Bonsall et al., 1989, Bonsall et al., 1992). The radiocarbon ages of limpet shells from the base of the midden (GU2600 7176 to 6815 cal BC), limpet shells from the top of the midden (GU2602 6090 ± 60 BP) and a red deer antler mattock (OxA3738 4770 to 4454 cal BC) from the top of the midden indicate that there was human occupation of the site in the middle Mesolithic period (Hedges et al., 1993, Bonsall et al., 1992). Stone tools were sparse in the midden and comprised of flint and quartz lithics, and a single shell ornament (Bonsall et al., 1992). A human infant, found in the most recent context, is reported in the 1989 preliminary report, but is not referred to in any subsequent studies of the site (Bonsall et al., 1989).

Eight samples of terrestrial fauna were made available for analysis by Professor Clive Bonsall of Edinburgh University. Species included in the baseline at Ulva are cattle (*Bos taurus*), sheep (*Ovis aries*) and red deer (*Cervus elaphus*). This dataset was procured to provide information about stable isotope variability between different environments (Ulva Island and mainland Oban) over short distances, and were included in the Oban dietary baseline in FRUITS where samples proved appropriate.

4.2.2 Sites located on the Orkney Islands

Figure 4.3 The locations of the Links of Notland (7), the Holm of Papa Westray (5), Crow Taing (3), and Pool Bay and Quoyness (9 and 10) on the Orkney Islands

Crow Taing, Sanday

This is the location of a single isolated human burial, dubbed 'the child in the sand'. The individual was discovered in February 2015 by a member of the public in the eroded beachfront of Crow Taing (figures 4.1 and 4.3) and was reported to Historic Environment Scotland who excavated the remains. The surrounding peninsular of Tofts Ness is rich in archaeological activity, spanning from the Neolithic (GU2209 4430 ± 70 BP (3339 to 2916 cal BC) from cattle bone collagen) to the Iron Age (GU2207 2510 ± 140 BP (971 to 235 cal BC) from cattle bone collagen) (Ambers, 2007: p147). The landscape is characterised by an abundance of mounds and enclosures; these structures bear evidence of human settlement and funerary practices which occurred throughout the chronology of Crow Taing (Dockrill, 2007a: p4-7). Excavation of the earliest sequences of one of these mounds, Mound 11, revealed three phases of occupation that were dated to the Neolithic-Bronze Age transition (GU2209 4430 ± 70 BP (3339 to 2916 cal BC) to GU2363 3380 ± 70 BP (1879 to 1510 cal BC), both samples from cattle bone collagen) (Ambers, 2007: p147), making the site of significance for this research in providing comparative information for diet at Early Neolithic and Late Neolithic sites in Scotland (Dockrill, 2007b: p13-14). The first three phases of the mound comprised deposits of limpet shell and animal bone (Dockrill, 2007b: p14). Cattle and sheep bones were abundant, with pig, red deer, seal and whale bones also present (Nicholson and Davies, 2007: p175-185). The presence of domesticated animals alongside small amounts of fish, shellfish and marine mammal remains indicates farming practices that may have been accompanied by periodic fishing or shellfish gathering (Nicholson and Davies, 2007: p195).

One fragment of human juvenile bone was provided for radiocarbon dating and stable isotope analysis by Dr. Alison Sheridan of National Museums Scotland. In the absence of available associated faunal remains, the faunal baseline for this individual's diet comprised the contemporary remains from Pool Bay and the modern local animals retrieved from Sanday where these sample were found to be appropriate.

The Holm of Papa Westray, Papa Westray

An abundance of faunal remains were excavated from the Holm of Papa Westray, from the tomb, the forecourt and the surrounding area. Some skeletal elements were dismissed as

being non-contemporary; rabbit, rat, horse and sheep bones were discovered in the uppermost layers of the site and were considered to be modern deposits (Harman, 2009). Contemporary faunal remains included examples of terrestrial mammals (sheep, cattle, red deer and a small amount of pig), shellfish (the vast majority limpets with >5% of the assemblage from other species), a large amount of fish (including, cod, haddock and pollock) and marine mammals (otters) (Harland and Parks, 2009, Harman, 2009, Maleszka-Ritchie, 2009).

Links of Noltland, Westray

Links of Noltland is a multi-period settlement located in a 104 ha area on the coast of Westray, Orkney. The site has been the focus of archaeological assessment and excavation since 1979, initially by Dr David Clarke of National Museums Scotland. It is now under the custody of EASE Archaeology, Westray. Stone structures, human, animal and plants remains, as well as cultural finds indicates persistent human occupation of the site between the Neolithic period and the Bronze Age. Key features of the Neolithic occupation are up to six structures, some including dividing walls and cupboards. Suggestions of hearths and dressers in these structures indicate these were domestic dwellings. Manufacturing on the site is represented by a possible kiln and evidence of bead production. A rich amount of cultural artefacts found on the site includes grooved-ware pottery, carved stone, bone tools and a stone figurine (Moore and Wilson, 2011: p21).

Domestic refuse and midden material provide some indication of the dietary habits at the Links of Noltland. The middens include the remains of domestic animals such as cattle (*Bos taurus*), sheep (*Ovis aries*) and pig (*Sus scrofa*) (Moore and Wilson, 2011: p8). Wild animals were also present at the site. These could have also contributed to the diet of the inhabitants and included red deer (*Cervus elaphus*) and various remains of fish and birds; however, it is unclear as to whether these animals were hunted for meat or whether they died of natural causes on-site (Fraser, 2011: p50). Radiocarbon ages obtained from several of the examples of terrestrial animals indicate that the remains were deposited between 3400 and 1460 cal BC (Moore and Wilson, 2011). Human bone was found in the form of a single inhumation and several disturbed burials; however, this material was not available for destructive analysis.

The sample population from Links of Noltland analysed in this study comprised the remains of terrestrial mammals from below structure 9 (believed to be a domestic dwelling), located in area 5 at the site. Ten cattle (*Bos taurus*), 10 sheep (*Ovis aries*) and four red deer (*Cervus elaphus*) bone fragments were obtained for analysis, all of which date between 2500 and 2000 BC (Sheena Fraser, 2014, personal communication, 22 August). These measurements were utilised as the faunal baseline for human dietary reconstruction at the nearby site of the Holm of Papa Westray.

Pool Bay, Sanday

The location of the multi-period site at Pool Bay, Sanday (figures 4.1 and 4.3) is under threat of coastal erosion and has been identified as a high-priority site by SCAPE (Scottish Coastal Archaeology and the Problem of Erosion) (Wilson, 2003). The site is an eroding beachfront with exposed layers of a kitchen midden, dating from the Neolithic to the Norse periods. There is evidence of continual site occupation between these periods, with a possible brief hiatus in the Bronze Age. Excavation in 1988 revealed Neolithic structures that demonstrated settled occupation between 3500 BC and 2000 BC (Hunter, 1988). Samples were obtained from the earliest exposed contexts in order to ensure a sample population of Neolithic age. Fifteen bones were sampled and identified to be cattle (*Bos taurus*), pig (*Sus scrofa*) and sheep/goat (*Ovis aries/Capra aegagrus hircus*). These terrestrial mammal samples were used to provide the stable isotope baseline for the dietary reconstruction of a child recovered at Crow Taing, and an unidentified human at Quoyness, both on Sanday.

Quoyness, Sanday

Quoyness chambered cairn (figures 4.1 and 4.3) was excavated in the late 1860s by Farrer and Petrie, whereupon the poorly preserved remains of at least 12 human adults and juveniles of both sexes were recovered (Farrer, 1868). The site was later investigated in the early 1950s by Prof. V. Gordon Childe and the Ministry of Works. Finds from the tomb included pottery and the remains of cattle (*Bos Taurus*), sheep (*Ovis aries*) and red deer (*Cervus elaphus*) (Childe, 1952). The structure, the finds and the radiocarbon ages are recorded on the Canmore database and indicate the date of the site to be within the Neolithic period (3350 to

2450 cal BC) (https://canmore.org.uk/c14index/3395). One fragment of human bone was obtained from National Museums Scotland for radiocarbon dating and $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ isotope measurements. The stable isotope results were modelled using FRUITS to reconstruct human diet, in conjunction with the contemporary faunal baseline from Pool, Sanday.

4.2.3 Sites located on the north and north-east coasts of Scotland

Embo, Dornoch

The chambered cairn at Embo (figures 4.1 and 4.3) had been extensively disturbed and robbed before an official investigation and a later excavation was carried out (Henshall, 1956, Henshall and Wallace, 1963). The cairn was made up of a number of chambers and cists that contained human remains in a variety of funerary settings. Cremated bone and disarticulated bone, as well as adult, juvenile and infant burials were recorded (Henshall and Wallace, 1963). Finds, including a food vessel, corded ware, animal bone, fragments of bronze blades and jet beads. This material culture indicated the date of the site to be between the Neolithic to the Late Bronze Age. Radiocarbon dates on human bone, recorded on the Canmore database (https://canmore.org.uk/c14index/15376), range from the Neolithic to the very early Bronze Age (3520-3350 cal BC to 2900-1900 cal BC), however there are no associated stable isotope measurements available to correct these radiocarbon ages for any potential marine reservoir effect (https://canmore.org.uk/c14index/15376).

One fragment of human bone from this site was provided by National Museums Scotland for radiocarbon dating and stable isotope analysis. No associated animal remains were available, therefore, contemporary remains from Pool Bay, Sanday and modern local mammals were used to derive the stable isotope faunal baseline when reconstructing this individual's diet. The site is relatively understudied so the investigation of this individual and the resulting data presented in this thesis is likely to be a valuable addition to the record.

Loch Borralie Cave, Durness

Loch Borralie cave is an un-stratified cave site located on the north coast of Scotland, discovered in 1992 by Mr. Colin Coventry, a caver (figures 4.1 and 4.3). This site is not recorded on the Canmore database and has no published reports associated with it. The human and animal remains from the site are now curated by National Museums Scotland. The site was targeted for investigation for several reasons and an animal bone from the cave has previously been radiocarbon dated to the Mesolithic period (SUERC44164 6211 to 6063 cal BC). The collection contains carnivore remains that are rarely found in middens and there are associated human bones included in the skeletal assemblage.

Two human and four terrestrial mammal samples were obtained for analysis. Three samples were radiocarbon dated as well as analysed for $\delta^{13}C$ and $\delta^{15}N$ by isotope ratio mass spectrometry (IRMS): two human samples and one wildcat (*Felis silvestris*). Three samples were analysed by IRMS, but were not radiocarbon dated: two lynx (L*ynx lynx*) and one wolf (*Canis lupus*). The isotope measurements on the carnivores were used to investigate relative trophic level shifts between terrestrial herbivores and carnivores, under the proviso that no differences in isotope ratios are detected in sites over large geographical distances – any isotopic differences in faunal baselines due to spatial distance would indicate that the carnivores cannot be reliably compared against herbivores from different locations. The measurements from the human individuals (if they proved to be of Mesolithic origin) were to be used to reconstruct diet, employing appropriate archaeological and modern samples to derive stable isotope baselines.

Tulach an t'Sionach and the Tullochs of Assery A and B, Loch Calder

Tulach an t'Sionach, the Tulloch of Assery A and the Tulloch of Assery B were three chambered cairns located to the north of Loch Calder in Caithness (see figures 4.1 and 4.3). J.X.W.P. Corcoran excavated the cairns in 1961 since they would be flooded by development works carried out on the Loch. Previous work on the tombs includes an extensive excavation report (Corcoran, 1964), and an investigation into the chronology of the site using radiocarbon dating (Sharples, 1986), however no work has been carried out as of yet on the dietary habits of the people buried in the tombs. The tombs are notable because there are stark differences between the architecture of each tomb and the burial practices evident,

despite their close proximity to each other (max.700 m apart). It was initially suggested that there may have been large chronological gaps between the construction of each structure, although this assumption was tenuous and noted the lack of radiocarbon measurements to provide absolute dates (Corcoran, 1964). Later ^{14}C research dated the cairns to have been in use between 2835 to 3085 cal BC and argues that they were all built within the space of 200 years (Sharples, 1986). The distinct nature of the tombs, suggests that they may have been constructed by different communities, in light of this dietary reconstruction on the humans buried in each tomb would be interesting to investigate whether these people ate different diets as well as having different funerary practices.

Human remains (one skeletal element from each tomb) for stable isotope analysis and radiocarbon dating were provided by Dr. Alison Sheridan at National Museums Scotland. Animal bone was excavated from Tulach an t'Sionach, but was not noted in either of the other tombs. This animal bone comprised cattle, red deer, and dogs, with small fragments of unidentifiable bird and fish bone (Corcoran, 1964). The faunal assemblage was unavailable for sampling. This presented a problem, since sites in Orkney and the west coast could rely on nearby baselines, but these cairns are located on the north mainland coast of Scotland. Due to the lack of chronologically and geographically representative baseline from this site, Scotland-wide averages of all faunal measurements were used, with the acknowledgement that dietary interpretations were not as secure here as they were for sites such as Carding Mill Bay which has a fully representative baseline.

4.3 Sample Collection

There were three distinct categories of samples sources for this research: archaeological human bone which was understood to date to the Mesolithic and Neolithic periods from Scottish sites, archaeological faunal bone from contemporary sites, and modern animal bone and flesh samples from across Scotland. The following sections describe the sampling process for each of these categories.

4.3.1 Human Samples

Human bone samples were provided for analysis by Dr Alison Sheridan at National Museums Scotland and comprised twelve individuals from four sites. Of these sites, none had an associated faunal assemblage available for measurement; therefore, their dietary reconstruction depended on measurements of ancient fauna from contemporaneous sites to the human bones and modern fauna from local sites. An exception to this was an individual from Embo, Sutherland (GU40816); in this case, other baseline solutions had to be considered as no contemporary or local baseline samples were available for measurement (see chapter 6.4.2 for details on the baseline chosen for this site). A further two human bone samples were provided by Dr Andrew Kitchener at National Museums Scotland and one sample was provided by EASE Archaeology, Westray. These samples had not been dated, and therefore underwent radiocarbon dating as well as stable isotope analysis. These 15 samples were supplemented with four published radiocarbon and stable isotope measurements of humans from Carding Mill Bay to comprise a total human sample population of 19 individuals (see Table 4.2). The majority of the human samples (16) came from Neolithic sites c.3600 to 2700 BC. Two individuals were sampled from the suspected Mesolithic cave site of Loch Borralie, and one individual was sourced from the confirmed Mesolithic site of Cnoc Coig, enabling the comparison of human diet between the Scottish Mesolithic and Neolithic periods.

Table 4.2 Summary information for human bone samples. All samples with prefix OxA are after Schulting and Richards (2002).

Sample ID	**Site**	**Radiocarbon age (^{14}C years BP ± 1σ)**	**Calibrated age range 2σ (Cal BC)**
OxA-7663	Carding Mill Bay	4800 ±50	3670-3380
OxA-7664	Carding Mill Bay	4830 ±45	3770-3520
OxA-7665	Carding Mill Bay	4690 ±40	3630-3370
OxA-7890	Carding Mill Bay	4330 ±60	3270-2710
GU-40827	Cnoc Coig	Mesolithic (to be dated)	See chapter 6
OxA-8004	Cnoc Coig	5740 ±65	4330-4040
OxA-8014	Cnoc Coig	5495 ±55	4020-3770
OxA-8019	Cnoc Coig	5615 ±45	4200-3960
GU-36227	Loch Borralie	Mesolithic? (to be dated)	See chapter 6
GU-36228	Loch Borralie	Mesolithic? (to be dated)	See chapter 6
GU-40816	Embo	Neolithic (to be dated)	See chapter 6
GU-40818	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40819	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40820	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40821	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40822	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40823	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40824	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40825	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40826	Raschoille Cave	Neolithic (to be dated)	See chapter 6
GU-40817	Quoyness	Neolithic (to be dated)	See chapter 6

4.3.2 Dietary Baseline Samples

It was necessary for dietary reconstruction using stable isotopes to build an archaeological faunal baseline that represented all species found on each archaeological site included in this study. Eight species of fauna were targeted for sampling (Table 4.3), which represented

animals commonly found at caves and midden sites, and are understood to be major components of the late Mesolithic and Early Neolithic diets (Mellars and Payne, 1971, Bonsall et al., 1989, Connock et al., 1991, Balasse et al., 2006, Pickard and Bonsall, 2014). Samples were obtained from Edinburgh University, Glasgow Museums Resource Centre (GMRC), EASE Archaeology in Orkney, and National Museums Scotland. Up to ten examples of each species represented in each assemblage were selected for sampling. The extremely fragmentary nature of all of the remains at the sites made it impossible to identify unique individuals. Care was taken to choose bone which was macroscopically well preserved and free from pathological lesions: pathology is an important diagnostic tool which can indicate the age, health and/or purpose of an animal, and it is appropriate to preserve these markers.

Table 4.3 Summary information of archaeological faunal samples

Sample ID	**Species**	**Site**
GU-36227	Wildcat *(Felis silvestris)*	Loch Borralie, Durness
GUsi-3482	Lynx *(Lynx lynx)*	Loch Borralie, Durness
GUsi-3483	Lynx *(Lynx lynx)*	Loch Borralie, Durness
GUsi-3484	Wolf *(Canis lupus)*	Loch Borralie, Durness
GUsi-3485	Roe deer *(Capreolus capreolus)*	Risga, Loch Sunart
GUsi-3486	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3487	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3488	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3489	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3490	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3491	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3492	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3493	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3494	Red deer *(Cervus elaphus)*	Risga, Loch Sunart
GUsi-3495	Pig *(Sus scrofa)*	Risga, Loch Sunart
GUsi-3496	Pig *(Sus scrofa)*	Risga, Loch Sunart
GUsi-3497	medium mammal (Ovis aries or *Capreolus capreolus)*	Carding Mill Bay, Oban

Sample ID	Species	Site
GUsi-3498	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3499	Pig *(Sus scrofa)*	Carding Mill Bay, Oban
GUsi-3500	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3501	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3502	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3503	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3504	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3505	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3506	large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3507	medium mammal (Ovis aries or *Capreolus capreolus)*	Carding Mill Bay, Oban
GUsi-3508	Large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3509	Red deer *(Cervus elaphus)*	Carding Mill Bay, Oban
GUsi-3510	Pig *(Sus scrofa)*	Carding Mill Bay, Oban
GUsi-3511	Large mammal *(Cervus elaphus or Bos taurus)*	Carding Mill Bay, Oban
GUsi-3512	Medium mammal (Ovis aries or *Capreolus capreolus)*	Carding Mill Bay, Oban
GUsi-3518	Sheep/goat *(Ovis aries or Capra aegagrus)*	Pool, Sanday
GUsi-3519	Sheep/goat *(Ovis aries or Capra aegagrus)*	Pool, Sanday
GUsi-3520	Cattle *(Bos taurus)*	Pool, Sanday

Sample ID	Species	Site
GUsi-3521	Cattle *(Bos taurus)*	Pool, Sanday
GUsi-3522	Cattle *(Bos taurus)*	Pool, Sanday
GUsi-3523	Cattle *(Bos taurus)*	Pool, Sanday
GUsi-3524	Pig *(Sus scrofa)*	Pool, Sanday
GUsi-3525	Probable cattle *(Bos taurus)*	Pool, Sanday
GUsi-3526	Probable cattle *(Bos taurus)*	Pool, Sanday
GUsi-3527	probable sheep/goat *(Ovis aries or Capra aegagrus)*	Pool, Sanday
GUsi-3528	probable sheep/goat *(Ovis aries or Capra aegagrus)*	Pool, Sanday
GUsi-3529	probable sheep/goat *(Ovis aries or Capra aegagrus)*	Pool, Sanday
GUsi-3530	Probable cattle *(Bos taurus)*	Pool, Sanday
GUsi-3531	Probable cattle *(Bos taurus)*	Pool, Sanday
GUsi-3532	Cattle *(Bos taurus)*	Pool, Sanday
GUsi-3610	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3611	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3612	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3613	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3614	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3615	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3616	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3617	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3618	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3619	Cattle *(Bos taurus)*	Links of Noltland, Westray
GUsi-3620	Red deer *(Cervus elaphus)*	Links of Noltland, Westray
GUsi-3621	Red deer *(Cervus elaphus)*	Links of Noltland, Westray
GUsi-3622	Red deer *(Cervus elaphus)*	Links of Noltland, Westray
GUsi-3623	Red deer *(Cervus elaphus)*	Links of Noltland, Westray
GUsi-3624	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3625	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3626	Sheep *(Ovis aries)*	Links of Noltland, Westray

Sample ID	Species	Site
GUsi-3627	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3628	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3629	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3630	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3631	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3632	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3633	Sheep *(Ovis aries)*	Links of Noltland, Westray
GUsi-3748	Red deer *(Cervus elaphus)*	Ulva Cave, Ulva
GUsi-3849	Cattle *(Bos taurus)*	Ulva Cave, Ulva
GUsi-3850	Cattle *(Bos taurus)*	Ulva Cave, Ulva
GUsi-3851	Cattle *(Bos taurus)*	Ulva Cave, Ulva
GUsi-3852	Red deer *(Cervus elaphus)*	Ulva Cave, Ulva
GUsi-3853	Red deer *(Cervus elaphus)*	Ulva Cave, Ulva
GUsi-3854	Sheep *(Ovis aries)*	Ulva Cave, Ulva
GUsi-3855	Red deer *(Cervus elaphus)*	Ulva Cave, Ulva

4.3.3 Modern Samples

Figure 4.4 Geographical location of all modern study sites (orange diamonds) throughout Scotland in relation to archaeological sites (blue circles) (Legend codes are detailed in table 4.4)

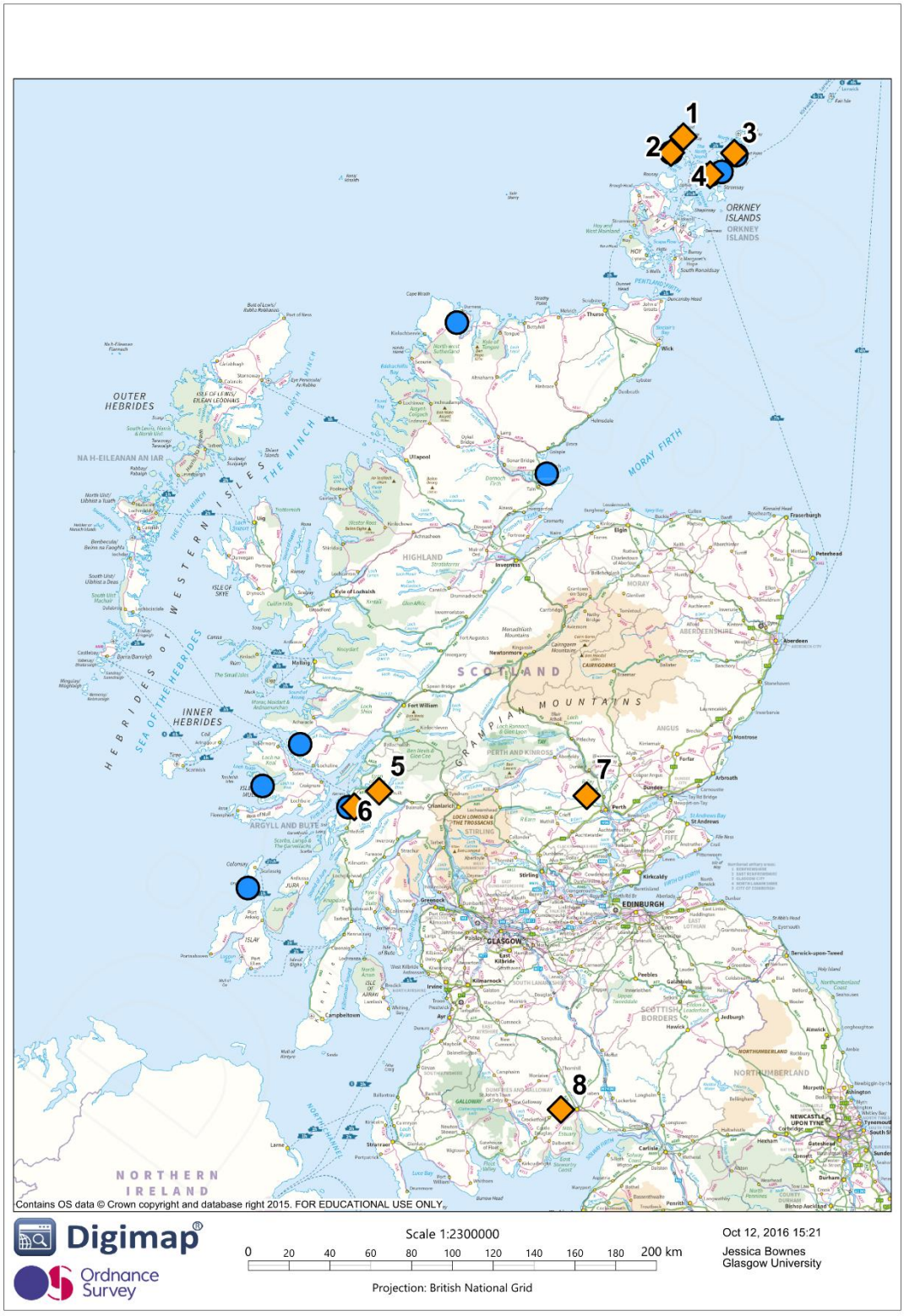


Figure 4.5 Geographical location of all sampling areas of Scotia 0125S survey

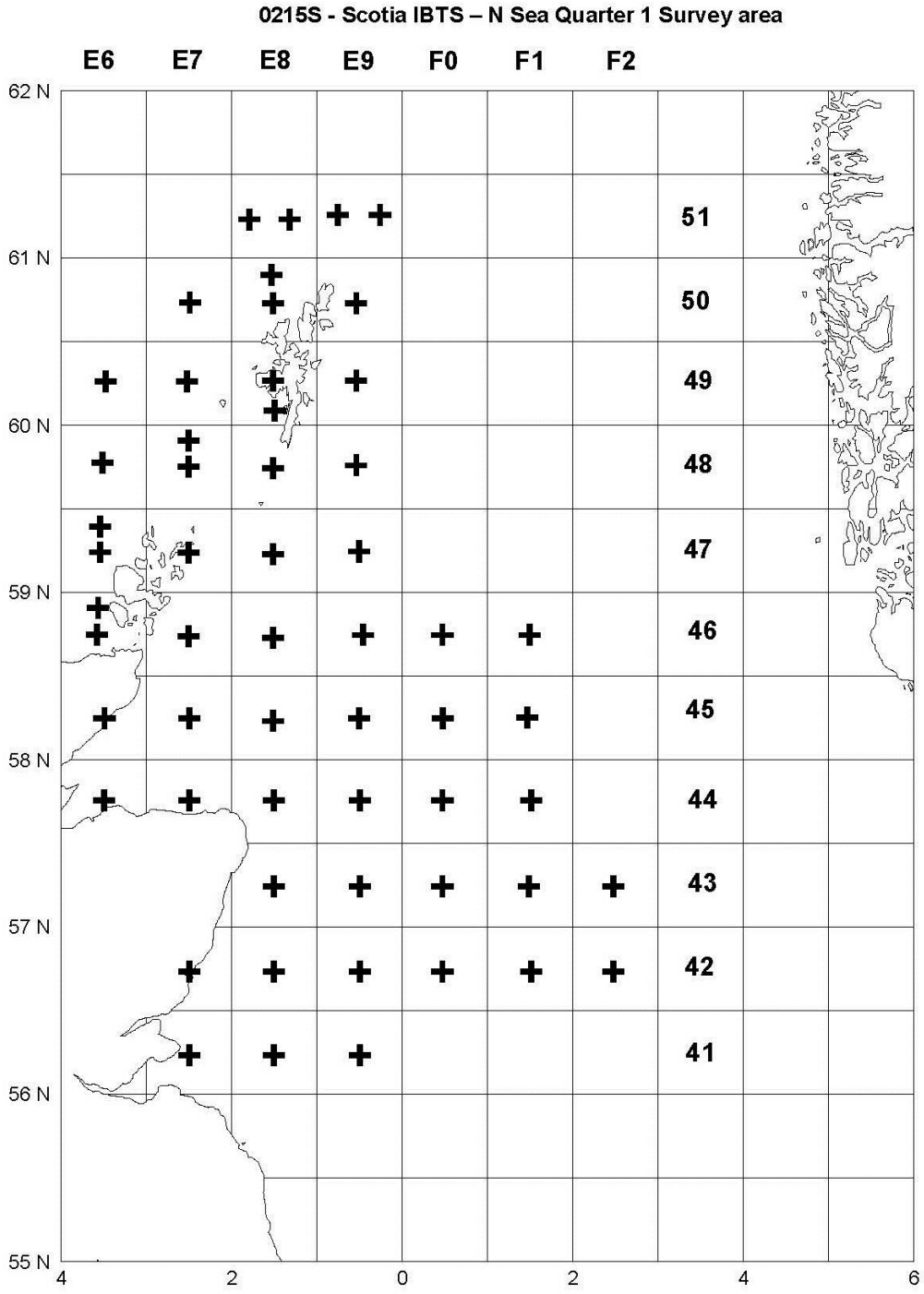


Table 4.4 Summary information for all modern sites shown in figure 4.4 in alphabetical order

Site Code	Figure 4.4 Legend	Site Name	Geographical Location	UK National Grid Reference
AB	5	Airds Bay	Oban	NM 997 321
BMC	8	Blackface Meat Company	Dumfries	NX 887 781
GCP	3	G & C Parker	Sanday	HY 737 441
GB	2	Grobust Bay	Westray	HY 428 493
HGO	7	Hugh Grierson Organic	Perth	NO 014 229
PL	4	Pool Bay	Sanday	HY619 379
STB	2	St. Boniface	Papa Westray	HY 487 527
SAM	6	The Scottish Association for Marine Science	Oban	NM 880 340

Modern terrestrial bone isotope values had to be comparable to the archaeological bone values so that the modern data would be suitable for inclusion in the archaeological faunal baseline. If the isotope values of a modern population did not significantly overlap with the same archaeological species, this would indicate a difference in diet between the modern and ancient populations (see Chapter 3.2 for further information). Species chosen were analogous to the species present in late Mesolithic and early Neolithic sites (Table 4.3). Terrestrial herbivores which were fed a supplemented diet typical of modern farming methods such as a grain based, or mixed feed diet would produce stable isotope data that would not be suitable for comparison against an archaeological population: prehistoric domesticates would have been raised on pasture, without the artificial dietary additives and fertilisers associated with modern farming. Therefore, modern bone was sourced from farms which only used natural and organic methods of raising animals. Samples were obtained from Hugh Grierson Organic, Perth and The Blackface Meat Company, Dumfries (Figure 4.4 and Table 4.4); these are farms that rear grass fed organic livestock, so the diet of these modern samples should better reflect that of ancient fauna. While these samples are comparable to ancient fauna in terms of their diet, they were reared some distance away from the two major archaeological locations, the west coast of Scotland and Orkney.

A selection of modern bone samples was sourced from sites which were geographically comparable to the archaeological sites included in this research (figure 4.4). These included a seal washed up on a beach in Sanday, lambs from the same locale which had not yet been weaned from their grass-fed mothers, sperm whale bone stored at a residence in Kirkwall and cattle bones from a beach on Westray, which was the site of a farm over 100 years ago (see Table 4.5 for a summary of terrestrial samples). The $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values of these samples will represent the local environment of Orkney, and can be used in conjunction with the archaeological bone to determine whether bone sampled from Hugh Grierson Organic, Perth and The Blackface Meat Company, Dumfries can be included in the faunal baseline.

Table 4.5 Summary information of modern terrestrial samples (see Figure 4.4 for modern site locations)

Site	**Species**	**Number of samples**	**Tissues analysed**
Hugh Grierson Organic, Perth	Cattle *(Bos taurus)*	3	Bone collagen, lipid extracted bone collagen, flesh and lipid extracted flesh
	Sheep *(Ovis aries)*	7	
Blackface Meat Company, Dumfries	Roe deer *(Capreolus capreolus)*	10	Bone collagen, lipid extracted bone collagen, flesh and lipid extracted flesh
	Red deer *(Cervus elaphus)*	10	
G & C Parker, Sanday	Un-weaned lamb *(Ovis aries)*	2	Bone collagen
	Lamb *(Ovis aries)*	1	
	Sheep *(Ovis aries)*	1	
Grobust Bay, Westray	Cattle (Bos taurus)	3	Bone collagen

A modern marine baseline was created with a focus on fish and shellfish species that are common on Mesolithic and Neolithic sites, but for which the edible portion is consumed and

does not survive in the archaeological record. There is a large variety of fish and shellfish species that are found on the archaeological sites included in this research (see individual descriptors for each site in section 6.4.2), however it was not possible to collect sample of each. To ensure the most representative marine baselines were created the most abundantly represented species were collected. The flesh of four species of shellfish and the flesh and bone collagen of three species of fish were sampled. See Table 4.6 for a summary of marine samples. Shellfish were sampled from the Oban and Orkney coastlines to take into account potential natural geographic isotopic variation and to match the archaeological sampling sites. Fish were collected by Marine Scotland from stations around Orkney during Scotia survey 0215S during January and February 2015 (see Figure 4.5).

Some archaeological sites contained evidence for the consumption of marine mammals (see section 6.4.2), therefore examples of species that were present were also collected for analysis (Table 4.6). These samples were historic and had no flesh or lipids present in the bone, therefore they were collagen extracted to be added to the FRUITS models where appropriate.

Table 4.6 Summary information of modern marine samples (see Figure 4.5 for modern site locations).

Site	**Species**	**Number of individuals**	**Tissues analysed**
North sea	Cod *(Gadus morhua)*	10	Bone collagen, lipid extracted bone collagen, flesh and lipid extracted flesh
	Haddock *(Melanogrammus aeglefinus)*	10	
	Pollock (*Pollachius pollachius*)	10	
Airds Bay, Oban	Limpet *(Patella vulgata)*	7	Flesh and lipid extracted flesh
	Mussel *(Mytilus edulis)*	8	

Site	Species	Number of individuals	Tissues analysed
	Cockle *(Cerastoderma edule)*	3	
	Winkle (Littorina littorea)	7	
The Scottish Association for Marine Science, Oban	Limpet *(Patella vulgata)*	6	Flesh and lipid extracted flesh
	Cockle *(Cerastoderma edule)*	8	
	Winkle (Littorina littorea)	9	
St Boniface, Papa Westray	Limpet *(Patella vulgata)*	9	Flesh and lipid extracted flesh
	Mussel *(Mytilus edulis)*	8	
	Winkle *(Littorina littorea)*	9	
Grobust Bay, Westray	Limpet *(Patella vulgata)*	10	Flesh and lipid extracted flesh
	Winkle *(Littorina littorea)*	10	
Pool Bay, Sanday	Limpet *(Patella vulgata)*	6	Flesh and lipid extracted flesh
	Mussel *(Mytilus edulis)*	1	
	Winkle *(Littorina littorea)*	10	
Sanday	Seal	1	Bone collagen
Sanday	Otter	1	Bone collagen
Kirkwall	Sperm whale	1	Bone collagen

4.4 Method Development for Modern Samples

The presence of lipids, which have lower $\delta^{13}C$ values relative to the whole flesh in shellfish meat, necessitates the removal of these compounds by solvent extraction before isotope analysis. This extraction step; however, has an unpredictable effect on $\delta^{15}N$ ratios (Pinnegar & Polunin, 1999; Post et al, 2007; Ryan et al, 2012), therefore samples were split into two fractions, with the whole fraction providing the $\delta^{15}N$values and the $\delta^{13}C$ values taken from the lipid extracted fraction.

Though Bligh and Dyer's (1959) method of extracting lipids from fish is widely applied as a standard method, there are many variations and deviations which employ a range of different equipment and solvent systems (Folch et al., 1957, Hubbard et al., 1977, Lee et al., 1996). It is for this reason that a method testing experiment was undertaken in order to identify the most effective and efficient method of extracting lipids from shellfish for this project. The first method used a soxhlet apparatus to remove lipids, and the second used a sonic bath. The solvent system was varied during method development as there is considerable debate as to which is most successful in removing lipids. Non-chlorinated systems were not considered as these have been shown to be ineffective in producing a total lipid extract (Gunnlaugsdottir and Ackman, 1993). Two systems were tested; dichloromethane:methanol 2:1 and chloroform:methanol 2:1 which was shown by Logan and Lutcavage (2008) to be effective in removing lipids from fish tissue for the purpose of $\delta^{13}C$ and $\delta^{15}N$ isotope analysis for dietary reconstruction. Sample state was varied, and shellfish were either whole or cut up into at least three distinct parts before freeze drying, or ground with a pestle and mortar after freeze drying. Mussels and limpets from Parton, Cumbria were extracted to test for any difference in extraction effectiveness according to species.

The weight of flesh samples was measured before and after extraction to give an indication of whether lipids were removed. Based on the results of the experimental extraction, it was decided that dichloromethane:methanol with a soxhlet apparatus would be used to extract lipids from flesh, with samples cut up into fine pieces after freeze drying. There was very little difference between the effectiveness of either cutting or grinding the samples, however grinding samples resulted in a small amount of sample loss (see Figure 4.7) and there were issues of cross contamination of samples which were not a concern in samples which were cut. The extraction process, regardless of method or solvent system, proved very ineffective

in whole limpet samples, suggesting the presence of an impermeable membrane protecting the flesh.

A soxhlet apparatus was chosen for flesh samples because there were concerns over sample loss when using a sonic bath. When using a sonic bath, samples were placed in 20 ml solvent system within glass vials and sonicated for 30 minutes before the solution was decanted. This was repeated twice more before the sample was dried down and weighed. Each time the solvent solution and extracted materials were removed from the sample tube, removal of small amounts of sample was unavoidable, particularly with cut and ground samples. Therefore, despite the data suggesting in most cases that the sonic bath system was more effective (see Figures 4.6 and 4.7), this can be considered unreliable since some sample loss occurred during each extraction phase. Sonicated crushed bone samples; however, were not affected by the same issues of sample loss, therefore bones were extracted in this way because this method is more time effective than soxhlet extraction.

Figure 4.6 Experimental lipid extraction of limpets, comparing different samples states, solvent systems and laboratory equipment

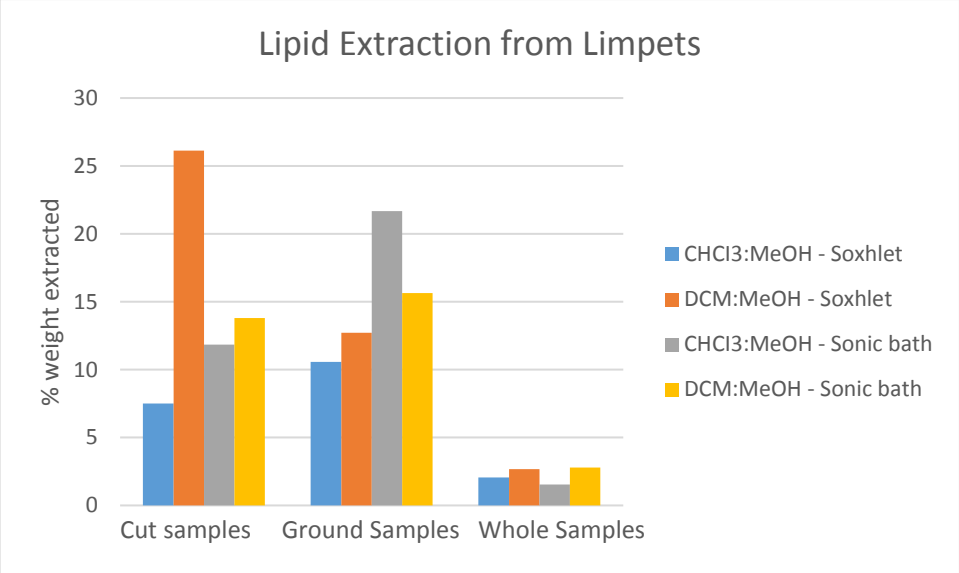
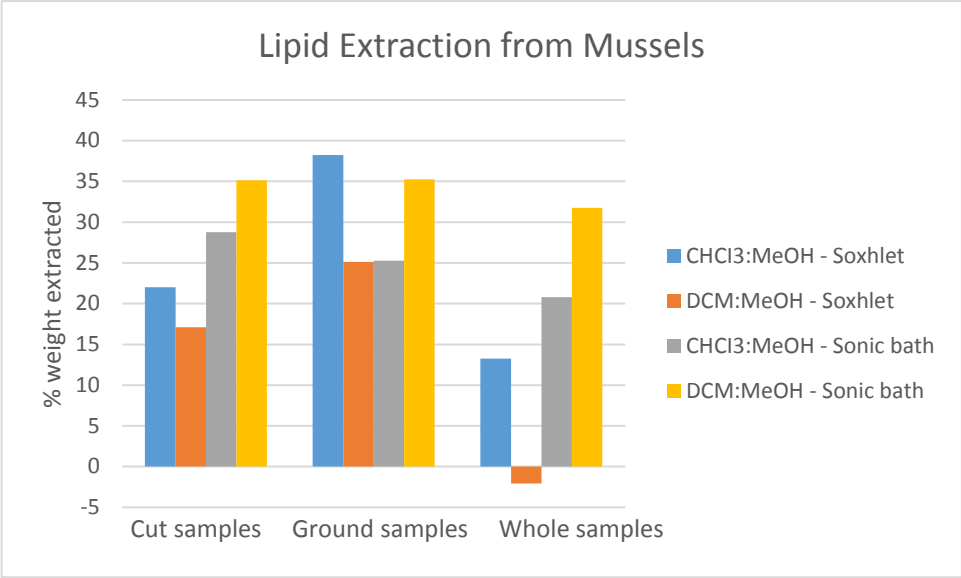


Figure 4.7 Experimental lipid extraction of mussels, comparing different samples states, solvent systems and laboratory equipment



Since dichloromethane is more volatile than chloroform, it was much more effective in the soxhlet apparatus which relies on cycling the solvents around the sample by evaporation and condensation. The dichloromethane:methanol system cycled more frequently than the chloroform:methanol system and, as a result, the former resulted in a clear wash through at the end of the process whereas the latter remained cloudy and coloured as the solvent collected in the extraction chamber containing the sample. This indicates that dichloromethane was the preferred non-polar solvent in the solvent system.

To test the efficacy of the chosen methods in removing lipids from flesh and bone, three samples of bone and nine samples of flesh were subject to repeat extraction and measurement using IRMS. This involved pre-treating the material and measuring a sub-sample before the sample was subject to a second extraction and sub-sampling. Flesh was extracted and sub-sampled three times in total and bone was extracted twice, until the $\delta^{13}C$ values did not differ between measured sub-samples, indicating that all lipids had been removed. Method testing was more rigorous for flesh samples because, whereas SUERC has a standard protocol for removing lipids from bone (Dunbar et al., 2016), there is no established method for flesh samples. See table 4.7 for the results of this method development which demonstrate that $\delta^{13}C$ values increase after the first lipid extraction and then remain stable after the second. This shows that all ^{12}C rich lipids were successfully removed at the first extraction.

Table 4.7 $\delta^{13}C$ values of deer and shellfish flesh and, subsequently, after the first, second and third time the sample was lipid extracted

Sample ID	Site	Extraction phase	Species	$\delta^{13}C$ ‰	%C	N	N%	C/N
GUsi3743 (deer 1)	Blackface Sheep Company	Unextracted	roe deer	-24.9	38.3	6.7	13.5	3.3
GUsi3733 (deer 1)	Blackface Sheep Company	First extraction	roe deer	-24.6	40.9	6.2	14.9	3.2
GUsi3926 (deer 1)	Blackface Sheep Company	Second extraction	roe deer	-24.5	38.3	6.7	13.6	3.3
GUsi3744 (deer 2)	Blackface Sheep Company	Unextracted	roe deer	-24.9	39.3	6.6	13.9	3.3
GUsi3734 (deer 2)	Blackface Sheep Company	First extraction	roe deer	-24.6	39.2	6.0	14.4	3.2
GUsi3927 (deer 2)	Blackface Sheep Company	Second extraction	roe deer	-24.3	39.3	6.3	14.0	3.3
GUsi3747 (deer 3)	Blackface Sheep Company	Unextracted	roe deer	-24.8	40.6	4.2	14.4	3.3
GUsi3737 (deer 3)	Blackface Sheep Company	First extraction	roe deer	-24.9	40.1	4.5	14.6	3.2
GUsi3928 (deer 3)	Blackface Sheep Company	Second extraction	roe deer	-24.2	35.5	4.6	12.5	3.3

Sample ID	Site	Extraction phase	Species	$\delta^{13}C$ ‰	%C	N	N%	C/N
GUsi3284 (limpet 1)	Westray, Links of Noltland	Unextracted	limpet	-17.3	37.3	7.1	11.3	3.9
GUsi3568 (limpet 1)	Westray, Links of Noltland	First extraction	limpet	-16.4	45.0	7.6	15.3	3.4
GUsi3569 (limpet 1)	Westray, Links of Noltland	Second extraction	limpet	-16.7	45.8	7.7	15.4	3.5
GUsi3570 (limpet 1)	Westray, Links of Noltland	Third extraction	limpet	-16.6	47.2	7.8	16.0	3.4
GUsi3178 (mussel 1)	Airds Bay	Unextracted	mussel	-18.3	35.1	8.4	9.9	4.1
GUsi3562 (mussel 1)	Airds Bay	First extraction	mussel	-16.7	45.9	9.5	15.6	3.4
GUsi3563 (mussel 1)	Airds Bay	Second extraction	mussel	-16.8	46.6	9.0	15.9	3.4
GUsi3564 (mussel 1)	Airds Bay	Third extraction	mussel	-16.8	47.7	9.6	16.2	3.4
GUsi3445 (winkle 1)	SAMS	Unextracted	winkle	-16.9	11.9	37.2	9.9	4.4
GUsi3565 (winkle 1)	SAMS	First extraction	winkle	-15.7	45.7	11.7	14.6	3.7
GUsi3566 (winkle 1)	SAMS	Second extraction	winkle	-15.9	45.1	11.9	14.0	3.8

Sample ID	Site	Extraction phase	Species	$\delta^{13}C$ ‰	%C	N	N%	C/N
GUsi3567 (winkle 1)	SAMS	Third extraction	winkle	-15.8	45.4	11.5	14.5	3.7

4.5 Pre-treatment Protocol

Several different types of sample were measured in this research, all of which required pre-treatment protocols that were appropriate for the tissue type and age of the sample. Chosen methods followed SUERC standard pre-treatment protocols or were modified from established procedures to customise the method to the sample material. Eight archaeological marine shellfish shells were sampled for radiocarbon dating. Collagen was extracted from 94 samples of archaeological bone from humans and eight species of fauna, and 70 samples of modern bone from 11 species. Flesh was sampled from 217 modern samples of seven species. All organic samples were selected and measured in order to investigate stable isotope values of dietary protein, or for radiocarbon dating as described below.

4.5.1 Archaeological Bone pre-treatment protocol

Samples weighing approximately 0.5-3 g were cut from bones which were macroscopically free from pathology, using a Dremel™ multi-tool with a saw blade, and surface contaminants were removed with a sanding bit. Pathology is an important diagnostic tool to assess the health of human or animal populations, therefore, samples affected by pathology were avoided in order to prevent the destruction of important diagnostic lesions.

For archaeological human and faunal bone, the SUERC standard pre-treatment method was used (Dunbar et al, 2016). This is a revised Longin (1971) method which was adapted by Brown et al. (1988) to prepare solid ‘collagen’ samples. The inorganic portion of the bone must be removed in order to isolate the ‘collagen’ for investigation (Ambrose and Norr, 1993). The pre-treatment process also used ultrafilters to remove any contaminants which might influence the isotope ratio results (Dunbar et al., 2016).

Samples were weighed and placed in 150 ml of 1M HCI at 20°C for approximately 24 hours, or until the bone had a jelly-like appearance, indicating that the inorganic portion of the bone was in solution. The HCI was decanted and 100 ml reverse osmosis water were added to the sample to create a slightly acidic solvent. The samples were then placed on a hotplate at 60°C in beakers covered with watch glasses for 2 hours or until all the collagen was dissolved. The sample was vacuum filtered through glass fibre filter paper, which had been decontaminated in a furnace prior to use. The filters were discarded and the 'collagen' solution was dried down to 20 ml in open beakers on the hotplate. Molecules larger than 30 kDa were then concentrated using Sartorius Vivaspin 20 30 kDa MWCO ultrafilters units. The sample solution was centrifuged through the filter for a minimum of 40 minutes until 5-7 ml of purified collagen solution remained above the filter. This process selectively removes potential contaminants, remaining lipids and degraded collagen to clean up the sample (Brock et al., 2007). The 5-7 ml of supernatant was then frozen and freeze dried to a solid sample while the filtrate was discarded.

4.5.2 Modern Bone pre-treatment protocol

Modern bone samples were separated into two fractions. One fraction was pre-treated using the SUERC standard collagen extraction method (Dunbar et al, 2016), and the second was subject to a lipid extraction step before collagen extraction. Lipid extraction was chosen to ensure that the modern bone $\delta^{13}C$ measurements were comparable to archaeological samples because lipids, which are depleted in ^{13}C compared to bone collagen, are not present in archaeological bone (Liden et al., 1995).

Modern bone samples from sheep, cattle, red deer and roe deer were kept frozen prior to pre-treatment and analysis. Samples were cut longitudinally into two equal fractions, adhering muscle tissue was removed with a scalpel and the bones were washed in ultra-pure water before they were dried in an oven overnight at 60°C. The 'whole bone' non-extracted portion was held aside for collagen extraction and $\delta^{15}N$ measurement, since lipid extraction using solvents has an unpredictable effect on nitrogen isotope ratios (Sotiropoulos et al., 2004). The second sample fraction was lipid extracted prior to collagen extraction for $\delta^{13}C$ measurement. Solvent extraction was chosen in preference to the use of ultrafilters as the former has been shown to remove a larger quantity of lipids while retaining a better collagen yield from each sample (Guiry et al., 2016).

To extract the lipid component from bone, the dried sample, was wrapped in aluminium foil and broken down into a powder using a hammer. Lipid extraction followed a variation of the established method at SUERC for removing lipids from modern bone samples for radiocarbon dating (Dunbar et al, 2016). The Dunbar et al. (2016) method uses chloroform/ethanol $CHCl_3/C_2H_5OH$ 2:1 (v/v), while the method employed here uses dichloromethane/methanol CH_2CI_2/CH_3OH 2:1 (v/v); this system was employed because CH_2Cl_2 has been shown to be slightly more effective at removing lipids from animal tissue samples (Cequier-Sánchez et al., 2008). The protocol involved extraction using a ultrasonic bath. The samples were placed into 20 ml screw-top vials and filled to the bottom of the vial neck with CH_2CI_2/CH_3OH 2:1 (v/v) and sonicated for 30 minutes. It was necessary to remove any residual solvent, so the sample was extracted with CH_3OH for a further 30 minutes, and finally it was rinsed repeatedly with ultra-pure water to remove residual CH_3OH before freeze-drying. The sample was then ready for collagen extraction as described above using the SUERC standard pre-treatment method before isotope ratio analysis by continuous flow IRMS (Dunbar, 2016).

4.5.3 Modern flesh pre-treatment protocol

Flesh samples from sheep, cattle, red deer and roe deer were stored frozen at -20°C prior to sampling. Samples were thawed and cleaned with ultra-pure water to rinse off any adhering particulates. Cleaned samples were then cut into at least two pieces, placed in vials, weighed and freeze dried, before grinding using a pestle and mortar. The homogenised sample was then split into two fractions, with one fraction solvent extracted for $\delta^{13}C$ measurement using the method applied to modern bone (section 4.5.2 above), and the second fraction kept back for $\delta^{15}N$ measurement.

The protocol for treating shellfish for $\delta^{13}C$ analysis involved lipid extraction using a Soxhlet apparatus. This method was chosen over the sonic bath method employed for modern bone because, in a trial extraction, it was not possible to change the solvent systems in the vials without significant sample loss – most likely due to the less dense nature of freeze dried flesh compared to bone. The sample was loaded into a glass fibre thimble and plugged with glass wool. The extraction was carried out over a period of six hours. It was necessary to remove any residual solvent, so the sample was extracted for six hours with CH_3OH using

the Soxhlet apparatus, and finally it was rinsed repeatedly with ultra-pure water to remove residual CH_3OH before freeze-drying.

4.6 ^{14}C samples pre-treatment protocol

Thirty samples were prepared for measurement of radiocarbon age by accelerator mass spectrometry (AMS) as follows: 1. Fourteen archaeological human bone samples from five sites. These measurements were required as the material had not previously been dated and an age was essential to place the samples in the appropriate chronological context. 2. Eight bone and eight shell samples from two secure contexts (four marine and four terrestrial samples per context) were obtained at Carding Mill Bay for the purpose of calculating a new ΔR value for the site. ΔR values have been calculated for Carding Mill Bay by Reimer (2002) and Ascough (2007), however there are different values for closely related contexts, and some values have large associated errors (e.g. ±91 years for context XIV). A ΔR value was required to provide a secure chronology for human remains at the site. This was carried out at Carding Mill Bay alone, since this was the only site where suitable human and paired marine/terrestrial samples for calculation of ΔR (c.f. Ascough et al, 2009; Cook et al, 2015) were available.

4.6.1 Bone collagen

Samples, pre-treated as described above (Chapter 4.5.1), were combusted at 900°C in sealed quartz tubes containing copper oxide and silver foil to remove impurities and obtain CO_2. The CO_2 was then cryogenically purified and 3 ml sub-samples converted to graphite by reducing the gas to CO with zinc powder, and then solid C with iron powder (Slota et al. 1987). The solid carbon was then pressed into aluminium cathodes for AMS measurement as described in Dunbar et al, (2016).

4.6.2 Shell

Surface contaminants were removed from each shell by first manually cleaning in water and then sonicating in a beaker of reverse osmosis water. To remove surface contamination, 20% of the shell surface was removed using 1M HCl, followed by rinsing with reverse osmosis water and drying. The samples were homogenised using a pestle and mortar and 0.1g of material was taken and a further 20% of the surface was removed using 1M HCl. CO_2 was obtained from the sub-samples under vacuum by acid hydrolysis and then cryogenically purified. 3 ml sub-samples of CO_2 were graphitized for AMS measurement as describe above (Chapter 4.6.1).

4.7 AMS ^{14}C measurement

Samples pressed into cathodes were loaded onto a 134 position carousel, with three international and in-house standards measured for each seven unknown samples. The primary standard used was NBS Oxalic Acid II, and the secondary standards were humic acid and barley mash (see Tables 4.8 and 4.9). In-house background standards were mammoth bone for bone samples (Cook et al., 2012), or Icelandic doublespar for carbonate samples. Many of the SUERC background and in-house standards have been employed in the worldwide AMS laboratory inter-comparison studies: TIRI, VIRI and SIRI (Scott, 2003, Scott et al., 2010). Sample $^{14}C/^{13}C$ ratios were measured on a National Electrostatics Corporation (NEC) 5MV tandem accelerator mass spectrometer (SUERC) with carbon in the 4^+ charge state or on a 250 kV single stage accelerator mass spectrometer (SAMS).

Table 4.8 Fraction modern carbon values for background radiocarbon standards

Material	**Source**	**Standard type**	**Values ($F^{14}C$)**
Heidelberg wood	VIRI-K	Background	0.0015 ± 0.0007 $F^{14}C$
Mammoth bone	Latton Quarry, Wiltshire LQH12	Background	0.0029 ± 0.0008 $F^{14}C$
Icelandic doublespar	TIRI-F	Background	0.0015 ± 0.0002 $F^{14}C$

Table 4.9 Consensus values for international primary and in-house secondary radiocarbon standards

Material	Source	Standard type	Mean consensus values
Oxalic acid II (SRM-4990C)	National Institute of Standards and Technology	Primary	134.08 pMC
Barley mash	TIRI-A	In-house Secondary	1.1635 ± 0.0070 $F^{14}C$
Humic acid	SIRI	In-house Secondary	3371 ± 30 ^{14}C yr BP

4.8 Continuous Flow Isotope Ratio Mass Spectrometry measurement of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$

Prepared samples of bone collagen or flesh were weighed into tin capsules at 500-600 µg per sample for carbon and nitrogen measurements and 1000-1100 µg for sulfur measurements. Standards were also weighed out and measured to calibrate the instrument and normalize the analytical data, thus correcting for any linearity or drift with time in the instrument during measurement. There is a need to correct for linearity as a result of mass spectra peak broadening which is connected to the major ion beam current. Analytical drift is caused by variations in the measurements reported by an instrument which is used over a sustained period.

SUERC in-house standards used were gelatine, tryptophan, cysteine, methionine and sulphanilamide (Table 4.10), which have known values measured in relation to international standards. These standards have known $\delta^{13}C$, $\delta^{15}N$ and/or $\delta^{34}S$ values, and are chosen because of the fundamental similarities in their stable isotope values to the samples being analysed. They are all soluble and organic, and the broad range of isotopic values enables a good quality regression analysis to be calculated for sample normalisation.

Table 4.10 Known values of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ for in-house standards (based on V-PDB, AIR and, V-CDT, respectively). N/A = not applicable

Reference standard	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	$\delta^{34}S$ (‰)
gelatine	-18.16	6.35	N/A
tryptophan	-25.24	7.24	N/A
cysteine	N/A	N/A	5.84
methionine	N/A	N/A	9.43
sulphanilamide	N/A	N/A	19.17

Samples and standards were measured on a Costech ECS 4010 elemental analyzer coupled to a Thermo Scientific Delta V Advantage continuous-flow isotope ratio mass spectrometer (CF-IRMS) using a Thermo Scientific Conflo IV. $\delta^{13}C$ and $\delta^{15}N$ standards were run after every ten samples, whereas $\delta^{34}S$ standards were run after every five samples, with a blank measured after each sample and/or standard. Data were reported in delta notation (per mil (‰)) to signify the expression of sample isotope ratios in relation to those of the international standards, and results are calculated using the formula $\delta X = 1000 \times \left(\frac{Rsample - Rstandard}{Rstandard}\right)$ where R is the ratio of the heavier to the lighter isotope. For all samples, carbon and nitrogen isotopes were measured together and sulfur separately. 1σ analytical precision for $\delta^{13}C$ analysis is ± 0.2‰, for $\delta^{15}N$ it is ± 0.3‰ and for $\delta^{34}S$ it is ± 0.6‰.

4.9 Quality Indicators

Bone diagenesis is the physical and chemical breakdown of bone following deposition, and relates to different processes by which the organic and inorganic portions can decay or alter. Mineral exchange with the burial environment can alter the composition of bone carbonates (Nelson et al., 1986), while collagen is at risk from breakdown, leaching and microbial attack, which may have unpredictable effects on the isotope ratios of carbon, nitrogen and other elements within it (Tuross et al., 1988). ^{14}C is also at risk from diagenesis as exogenous carbon of a different age to the bone can be fixed into the sample while it is in-situ or during post-excavation treatment. The pre-treatment protocol is designed to remove contaminants and degraded collagen; however, diagenetic effects are not always macroscopically

detectable, so quality control indicators are applied to detect samples which must be excluded from the research discussion. Quality indicators are employed after collagen extraction and before analytical measurement. The collagen yield from each bone sample must be at least 1% to ensure that the original sample contained an adequate quantity of bone collagen, indicating good preservation of the original bone (Van Klinken, 1999). After measurement by IRMS, C/N, C/S and N/S ratios are checked for quality assurance, and must fall within the range of ratios obtained from fresh bone collagen that is free of contamination and diagenetic change; these are 2.9-3.6 for C/N, (DeNiro and Schoeninger, 1983), 100-300 for C/S and 300-900 for N/S (Nehlich and Richards, 2009).

4.10 Data Analysis

4.10.1 $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ Isotope Ratio Measurements to Reconstruct Diet

For dietary reconstruction, normalised stable isotope data are plotted onto bivariate scatter graphs. To evaluate consumption of animal products, freshwater and marine resources and terrestrial plants, $\delta^{13}C$ is plotted on the x-axis, while $\delta^{15}N$ is plotted on the y-axis. This enables interpretation of diet through the comparison of different individuals and species in terms of $\delta^{15}N$ trophic level shift and distinct $\delta^{13}C$ values.

For a review of the literature concerning the interpretation of carbon and nitrogen isotope values, see Chapter 3. To summarise the concept, carbon isotope measurements are used to distinguish between marine- and terrestrial-based diets: carbon reservoirs at the base of the food chain for freshwater, marine and terrestrial environments have distinct $\delta^{13}C$ values that are reflected in consumers' body tissue. Nitrogen isotope values reflect a consumer's position in the food chain. Plants and animals preferentially excrete the lighter ^{14}N isotope in their waste, retaining the heavier ^{15}N isotope in their organic tissues. This preferential fractionation of the lighter isotope creates a step-wise enrichment in ^{15}N along the food chain, with bone collagen from carnivores and omnivores having nitrogen isotope values that are enriched in ^{15}N. Nitrogen isotope values of carnivorous fish in freshwater and marine environments have bone collagen nitrogen isotope values that are far more enriched in ^{15}N compared to carnivores in terrestrial environments because water-based food chains are much longer than land-based chains; these enriched values are reflected in humans and

terrestrial fauna that consume fauna from these habitats. See Chapter 3.2.1 for discussion on typical isotope value ranges for human and animal bone collagen and flesh.

To distinguish between freshwater, marine and terrestrial diets, $\delta^{13}C$ is plotted on the x-axis, while $\delta^{34}S$ is plotted on the y-axis. The analysis of variation in $\delta^{34}S$ isotope data may help to distinguish these diets where there may be some ambiguity in the carbon and nitrogen data: overlaps have been observed in $\delta^{15}N$ values of terrestrial herbivores and freshwater fish and in $\delta^{13}C$ values of freshwater and marine fauna that can be clarified through the analysis of $\delta^{34}S$ (Sayle et al., 2014). Values of $\delta^{34}S$ vary in different environments: ocean particulate organic matter = +17 to +21‰, lake particulate organic matter = -22 to +20‰ and terrestrial vegetation = -5 to +22‰ (Peterson and Fry, 1987). Because of the considerable overlap in these ranges, $\delta^{34}S$ must be utilised in conjunction with $\delta^{15}N$ and $\delta^{13}C$ measurements in order to make confident assertions about diet (Privat et al., 2007, Craig et al., 2006).

4.10.2 Calculating percentage marine contribution to palaeo-diet

Estimates of the abundance of dietary protein contributions to human diet from marine fish, marine shellfish, terrestrial animals and terrestrial plants were calculated using FRUITS V2.1.1 (see Chapter 3.4 for an explanation of FRUITS). For each model, food values were made up from the mean isotope values of local archaeological fauna and were supplemented with modern faunal isotope values where they were comparable to local archaeological values. Modern $\delta^{13}C$ values were adjusted to take into account the change in isotope ratios caused by the Suess Effect, whereby organisms are depleted in ^{13}C compared to ancient samples as a result of the release of carbon from fossil fuel burning in the last two centuries (Suess, 1958). Suess Effect offsets were 0.86‰ for marine values and 1.5‰ for terrestrial values (Beavan Athfield et al., 2008). The mean faunal baseline values were then converted to food values using tailored $\Delta^{13}C_{protein\text{-}collagen}$ and $\Delta^{15}N_{protein\text{-}collagen}$ offset values, calculated using the modern flesh and bone collagen measurements. The corrected stable isotope information was then entered into a routed FRUITS model with diet-to-consumer tissue isotopic offset values of $\delta^{13}C = 1\pm1$ and $\delta^{15}N = 5.5\pm0.5$. 'Routed' in this context denotes the assumption that dietary protein carbon and nitrogen is incorporated into bone collagen, and therefore, the isotopic measurement of bone collagen reveals the source of dietary protein (Ambrose and Norr, 1993).

Quality indicators were carried out to ensure the reliability of each dietary reconstruction. After each model ran, it was necessary to check that it had fully converged: less than 10,000 reported updates indicated an inferior model (Fernandes, pers. Comm., 7 Sept 2015) . The error values on the estimated dietary contributions are also checked for precision and accuracy. Values of greater that 20% uncertainty on an estimate indicate that the calculated mean value for that food group is inaccurate and that the model is not therefore a reliable reflection of dietary composition. The careful consideration of likely food groups using archaeological evidence at each site mitigates against the chance of a model returning an inaccurate estimate.

4.10.3 Modelling ^{14}C Reservoir Effects

In mixed marine/terrestrial diets, old carbon from the marine reservoir is incorporated into the bone collagen, along with contemporary carbon from the terrestrial environment. In order to calculate the appropriate marine reservoir offset to apply to existing radiocarbon dated human remains, it is necessary to calculate the % marine resource contribution to the diet. With this value obtained from the FRUITS models, any human radiocarbon age, where the sample showed a marine contribution to the diet, was recalibrated. The method used followed Cook et al. (2015); briefly this comprises using the derived value for percentage marine diet and the contemporary local ΔR value, and recalibrating the date using the mixed Marine 13/IntCal 13 radiocarbon calibration curves. Data were reported in ^{14}C yrs BP, and calibrated using Oxcal 4.2 (Bronk Ramsey, 2009). Precision is reported at 1σ, and the value in years varies depending on where the age lies on the radiocarbon calibration curve.

In the case of Carding Mill Bay, a new ΔR value (-130 ± 34 ^{14}C yrs) was calculated using a multiple paired terrestrial/marine sample approach as described in Russell et al. (2015). This method involves using an interpolation of the IntCal13 and Marine13 curves, where the terrestrial ages are converted to model marine ages with errors. ΔR is the offset between modelled age and measured marine age. Multiple samples from discrete contexts (4 x terrestrial, 4 x marine) were radiocarbon dated, and those that passed a χ^2 test were employed to calculate ΔR for every possible pairing. The ΔR values and the associated errors for each context were determined by finding the weighted mean ΔR and calculating the standard error for predicted values.

Chapter 5: Results

5.1 Introduction

This chapter details the stable isotope values and radiocarbon measurements of all modern and archaeological samples in this study. After quality control indicators are considered and applied in section 5.2, the stable isotope data for all samples measured for this thesis is presented. The modern marine and terrestrial faunal samples are presented first in a series of tables. The average values of these measurements are summarised before the raw data is used to calculate the tissue offsets required for the FRUITS models of human diets which are considered in Chapter 6. Once the modern samples have been outlined, the stable isotope measurements of the archaeological sample faunal and human samples are introduced and summarised. Only the stable isotope data is considered in this chapter. The radiocarbon data is considered in Chapter 6. Since the calibration of each date depends on the outcome of each FRUITS model, it is essential that the stable isotope data are considered and the FRUITS models are created before the radiocarbon measurements can be addressed.

5.2 Quality control indicators

Poorly preserved or contaminated samples will not produce reliable stable isotope measurements. It is essential that any samples that were not of adequate quality were identified and removed from discussion using the appropriate quality control indicators. Quality control indicators following sample pre-treatment dictate that bone collagen yields below 1% of the whole sample weight indicate poorly preserved collagen (DeNiro, 1985). Three samples (GUsi3739, GUsi3849 and GUsi4479) were failed at pre-treatment, and therefore discarded and not measured by IRMS. For all other samples following IRMS measurement, quality control indicators for stable carbon and nitrogen isotopes were applied according to Van Klinken (1999): where the C/N atomic ratio is outside the range 2.9 to 3.6, this indicates potentially degraded or contaminated samples; all samples passed this quality test. There are currently no quality control indicators for fresh bone which contains lipid and muscle, but since these samples were not degraded and had not been exposed to a burial environment, sample quality control indicators were not necessary. Any unsuitable samples are underlined and excluded from discussion in later chapters.

Quality control indicators for sulfur isotope values for mammal bone collagen are C:S atomic ratio = 600±300 and N:S atomic ratio = 200±100 (Nehlich and Richards, 2009). No samples were outside of this criteria and therefore none were excluded from discussion. However, sulfur isotopes were measured on only a small number of archaeological faunal bone collagen samples. This research had originally intended to include sulfur as a third human dietary isotope proxy alongside carbon and nitrogen. Following initial sample measurements, though, it became apparent that sulfur isotope analysis of the ancient fauna in Scotland revealed a sea-spray effect, and therefore was not suitable as a dietary proxy.

5.3 Modern faunal samples from the marine and the terrestrial environments

Stable isotope measurements of modern marine and terrestrial animals were required for this research for three key reasons: 1) to produce local and species specific isotope tissue offsets in order to convert the archaeological faunal baseline values to the 'food group' values for the FRUITS models, 2) to test the hypothesis that comparable modern samples were suitable to supplement archaeological faunal isotope baselines for palaeodietary studies, and 3) to test the hypothesis that modern shellfish flesh could be used to model relative marine fish/marine shellfish/terrestrial herbivore contribution to human diet.

The stable isotope data for modern terrestrial herbivores are presented in Tables 5.1 to 5.4 and data for marine fish are presented in Tables 5.5 to 5.8. The data are presented in tables according to the four different tissue fractions analysed per sample individual: these fractions are bone collagen including the lipids, bone collagen, muscle including the lipids, muscle. Shellfish data are presented differently because there are only two tissue fractions: muscle including the lipids and muscle, and there were a larger number of samples then the herbivores and fish. Therefore, shellfish data are presented in Tables 5.9 to 5.16 and are grouped according to species and tissue fraction. Summary values of both modern marine and modern terrestrial faunal isotope data follow in section 5.3.5.

5.3.1 Terrestrial herbivore bone and muscle samples

The $\delta^{13}C$ measurements of the terrestrial faunal bone collagen including lipids ranged from -26.5 to -22.5‰ and μ = -24.8 ±0.7‰. The $\delta^{15}N$ measurements of all terrestrial bone collagen

including lipids ranged from 2.6 to 8.2‰ μ = 5.2 ±1.8‰. The $\delta^{13}C$ measurements of all terrestrial bone collagen ranged from -26.4 to -24.1‰ and μ = -24.9 ±0.6‰. The $\delta^{15}N$ measurements of the terrestrial faunal bone collagen ranged from 2.5 to 6.3‰ μ = 5.2 ±1.7‰.

The $\delta^{13}C$ measurements of the terrestrial muscle samples including lipids ranged from -30.4 to -26.3‰ and μ = -27.8 ±1.1‰. The $\delta^{15}N$ measurements of the terrestrial muscle samples including lipids ranged from 2.8 to 7.2‰ and μ = 5.4 ±1.7‰. The $\delta^{13}C$ measurements of the terrestrial muscle ranged from -28.2 to -25.6‰ and μ = -26.8 ±0.7‰. The $\delta^{15}N$ measurements of all terrestrial muscle ranged from 2.8 to 8.4‰ μ = 5.4 ±1.7‰.

Table 5.1 Stable carbon and nitrogen isotope values for samples of modern terrestrial herbivore bone collagen samples including lipids from Blackface Sheep Company, Hugh Grierson and C&G farms, and Grobust Bay Scotland.

Sample ID	**Species**	**Site name**	**$\delta^{13}C$ ‰**	**$\delta^{15}N$ ‰**	**%C**	**%N**	**C/N atomic ratio**
GUsi3743	roe deer1	Blackface Sheep Company	-24.9	6.7	38.3	13.5	3.3
GUsi3744	roe deer2	Blackface Sheep Company	-24.9	6.6	39.3	13.9	3.3
GUsi3745	roe deer3	Blackface Sheep Company	-24.9	6.2	40.7	14.6	3.3
GUsi3746	roe deer4	Blackface Sheep Company	-24.4	4.9	39.5	14.0	3.3
GUsi3747	roe deer5	Blackface Sheep Company	-24.8	4.2	40.6	14.4	3.3
GUsi3848	roe deer6	Blackface Sheep Company	-22.5	2.7	34.9	12.5	3.3
GUsi3849	roe deer7	Blackface Sheep Company	FAILED PRE-TREATMENT				
GUsi3750	roe deer8	Blackface Sheep Company	-26.5	2.6	38.3	13.6	3.3

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi3751	roe deer9	Blackface Sheep Company	-24.9	4.3	39.3	14.0	3.3
GUsi3752	roe deer10	Blackface Sheep Company	-24.5	4.9	43.9	15.7	3.3
GUsi4439	red deer1	Blackface Sheep Company	-24.2	3.0	41.5	15.1	3.2
GUsi4440	red deer2	Blackface Sheep Company	-24.6	3.0	40.3	14.7	3.2
GUsi4441	red deer3	Blackface Sheep Company	-23.9	3.8	40.1	14.6	3.2
GUsi4442	red deer4	Blackface Sheep Company	-24.9	5.1	40.5	14.7	3.2
GUsi4443	red deer5	Blackface Sheep Company	-24.7	3.1	40.7	14.7	3.2
GUsi4444	red deer6	Blackface Sheep Company	-24.3	4.0	38.9	14.1	3.2
GUsi4445	red deer7	Blackface Sheep Company	-24.5	3.1	41.1	14.8	3.2
GUsi4446	red deer8	Blackface Sheep Company	-24.5	4.5	41.5	15.0	3.2
GUsi4447	red deer9	Blackface Sheep Company	-24.2	4.1	40.6	14.7	3.2
GUsi4448	red deer10	Blackface Sheep Company	-24.3	2.7	42.0	15.2	3.2
GUsi4469	Cattle1	Hugh Grierson	-24.7	6.1	43.3	15.7	3.2
GUsi4470	Cattle2	Hugh Grierson	-24.6	6.3	38.9	14.1	3.2
GUsi4471	Cattle3	Hugh Grierson	-24.7	6.1	41.2	14.8	3.2
GUsi4472	Sheep1	Hugh Grierson	-25.5	7.2	42.6	15.0	3.3
GUsi4473	Sheep2	Hugh Grierson	-25.8	7.5	42.2	14.7	3.3
GUsi4474	Sheep3	Hugh Grierson	-25.7	8.0	44.0	15.6	3.3
GUsi4475	Sheep4	Hugh Grierson	-25.2	8.2	41.9	14.7	3.3

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4476	Sheep5	Hugh Grierson	-25.4	6.7	42.1	15.1	3.2
GUsi4477	Sheep6	Hugh Grierson	-25.5	8.0	40.7	14.4	3.3
GUsi4478	Sheep7	Hugh Grierson	-26.0	8.0	41.5	14.9	3.3
GUsi4479	Sheep8	Hugh Grierson	FAILED AT PRE-TREATMENT				

Table 5.2 Stable carbon and nitrogen isotope values for modern terrestrial herbivore bone collagen samples from Blackface Sheep Company, Hugh Grierson and C&G farms, and Grobust Bay Scotland.

Sample ID	**Species and individual number**	**Site name**	**$\delta^{13}C$ ‰**	**$\delta^{15}N$ ‰**	**%C**	**%N**	**C/N atomic ratio**
GUsi3733	roe deer1	Blackface Sheep Company	-24.6	6.2	40.9	14.9	3.2
GUsi3734	roe deer2	Blackface Sheep Company	-24.6	6.0	39.2	14.4	3.2
GUsi3735	roe deer3	Blackface Sheep Company	-24.9	6.3	39.8	14.5	3.2
GUsi3736	roe deer4	Blackface Sheep Company	-24.3	4.9	36.5	13.4	3.2
GUsi3737	roe deer5	Blackface Sheep Company	-24.9	4.5	40.1	14.6	3.2
GUsi3738	roe deer6	Blackface Sheep Company	-24.5	4.9	36.7	13.4	3.2
GUsi3739	roe deer7	Blackface Sheep Company	FAILED PRE-TREATMENT				
GUsi3740	roe deer8	Blackface Sheep Company	-26.4	2.5	34.6	12.6	3.2
GUsi3741	roe deer9	Blackface Sheep Company	-25.2	4.3	41.4	15.1	3.2
GUsi3742	roe deer10	Blackface Sheep Company	-24.5	4.8	41.9	15.3	3.2
GUsi4449	red deer1	Blackface Sheep Company	-24.4	2.8	40.2	14.6	3.2
GUsi4450	red deer2	Blackface Sheep Company	-24.1	2.8	40.5	14.7	3.2
GUsi4451	red deer3	Blackface Sheep Company	-24.1	3.2	43.4	15.7	3.2

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4452	red deer4	Blackface Sheep Company	-25.1	5.2	38.1	13.9	3.2
GUsi4453	red deer 5	Blackface Sheep Company	-24.4	3.1	39.6	14.4	3.2
GUsi4454	red deer 6	Blackface Sheep Company	-24.7	3.7	37.2	13.5	3.2
GUsi4455	red deer7	Blackface Sheep Company	-24.2	2.9	42.2	15.3	3.2
GUsi4456	red deer8	Blackface Sheep Company	-24.7	4.3	38.4	14.0	3.2
GUsi4457	red deer 9	Blackface Sheep Company	-25.0	3.6	33.8	12.3	3.2
GUsi4458	red deer 10	Blackface Sheep Company	-24.7	2.6	32.8	11.9	3.2
GUsi4480	Cattle1	Hugh Grierson	-24.6	5.3	32.0	11.6	3.2
GUsi4481	Cattle2	Hugh Grierson	-25.1	6.8	45.4	16.3	3.2
GUsi4482	Cattle3	Hugh Grierson	-25.0	7.0	36.8	13.3	3.2
GUsi4485	Sheep1	Hugh Grierson	-26.0	7.9	43.0	15.4	3.3
GUsi4486	Sheep2	Hugh Grierson	-26.3	8.2	41.2	14.8	3.2
GUsi4487	Sheep3	Hugh Grierson	-25.8	7.0	40.2	14.5	3.2
GUsi4488	Sheep4	Hugh Grierson	-24.6	6.2	39.8	14.5	3.2
GUsi4489	Sheep5	Hugh Grierson	-24.6	6.5	39.4	14.2	3.2
GUsi4490	Sheep6	Hugh Grierson	-26.0	6.6	39.7	14.4	3.2
GUsi4670	Sheep7	C&G	-21.1	9.8	35.3	12.6	3.3
GUsi4671	Lamb1	C&G	-25.2	7.1	36.8	13.5	3.2
GUsi4672	Lamb2	C&G	-24.7	7.8	35.5	12.7	3.3
GUsi4673	Lamb3	C&G	-24.5	6.8	37.7	13.5	3.3

Table 5.3 Stable carbon and nitrogen isotope values for samples of modern terrestrial herbivore muscle including lipids from Blackface Sheep Company and Hugh Grierson farms, Scotland.

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4030	roe deer1	Blackface Sheep Company	-27.6	7.2	45.3	12.9	4.1
GUsi4031	roe deer2	Blackface Sheep Company	-27.7	6.8	47.6	13.1	4.2
GUsi4032	roe deer3	Blackface Sheep Company	-28.3	6.2	47.8	12.8	4.4
GUsi4033	roe deer4	Blackface Sheep Company	-27.6	5.5	46.1	13.0	4.1
GUsi4034	roe deer5	Blackface Sheep Company	-28.3	4.2	47.2	13.2	4.2
GUsi4035	roe deer6	Blackface Sheep Company	-27.6	6.2	46.2	13.2	4.1
GUsi4036	roe deer7	Blackface Sheep Company	-28.6	3.6	42.6	12.2	4.1
GUsi4037	roe deer8	Blackface Sheep Company	-28.7	2.9	46.1	13.2	4.1
GUsi4038	roe deer9	Blackface Sheep Company	-28.3	4.9	46.6	12.8	4.3
GUsi4039	roe deer10	Blackface Sheep Company	-27.0	5.3	46.8	13.3	4.1
GUsi4459	red deer1	Blackface Sheep Company	-26.7	3.6	49.0	14.4	4.0
GUsi4460	red deer2	Blackface Sheep Company	-27.1	3.4	52.8	14.9	4.1
GUsi4461	red deer3	Blackface Sheep Company	-26.9	4.8	47.7	12.5	4.4
GUsi4462	red deer4	Blackface Sheep Company	-26.9	4.4	48.1	13.6	4.1

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4463	red deer5	Blackface Sheep Company	-27.0	3.4	49.9	14.2	4.1
GUsi4464	red deer6	Blackface Sheep Company	-27.0	4.2	49.4	13.7	4.2
GUsi4465	red deer7	Blackface Sheep Company	-26.7	3.3	50.2	14.7	4.0
GUsi4466	red deer8	Blackface Sheep Company	-26.6	3.4	48.5	14.3	4.0
GUsi4467	red deer9	Blackface Sheep Company	-26.7	3.8	50.9	14.8	4.0
GUsi4468	red deer10	Blackface Sheep Company	-26.3	2.8	48.8	14.6	3.9
GUsi4612	Cattle1	Hugh Grierson	-27.0	4.7	46.6	13.4	4.1
GUsi4613	Cattle2	Hugh Grierson	-27.5	5.9	49.4	13.8	4.2
GUsi4614	Cattle3	Hugh Grierson	-27.4	5.8	48.1	13.4	4.2
GUsi4615	Sheep1	Hugh Grierson	-28.3	7.4	48.5	14.2	4.0
GUsi4616	Sheep2	Hugh Grierson	-28.9	7.1	48.6	13.7	4.1
GUsi4617	Sheep3	Hugh Grierson	-29.6	8.2	51.9	11.8	5.1
GUsi4618	Sheep45	Hugh Grierson	-30.4	7.1	55.0	10.5	6.1
GUsi4619	Sheep6	Hugh Grierson	-30.3	8.5	55.8	11.1	5.8
GUsi4620	Sheep7	Hugh Grierson	-29.5	8.0	51.3	12.9	4.6

Table 5.4 Stable carbon and nitrogen isotope values for modern terrestrial herbivore muscle samples from Blackface Sheep Company and Hugh Grierson farms, Scotland.

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4996	roe deer1	Blackface sheep company	-26.9	8.0	46.4	14.8	3.7

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4997	roe deer2	Blackface sheep company	-26.7	7.5	46.7	14.7	3.7
GUsi4998	roe deer3	Blackface sheep company	-27.3	6.8	47.2	14.8	3.7
GUsi4999	roe deer4	Blackface sheep company	-26.7	6.2	47.1	14.8	3.7
GUsi5000	roe deer5	Blackface sheep company	-27.4	4.5	47.3	15.0	3.7
GUsi5001	roe deer6	Blackface sheep company	-26.9	6.5	46.9	14.8	3.7
GUsi5002	roe deer7	Blackface sheep company	-28.0	4.0	47.5	15.0	3.7
GUsi5003	roe deer8	Blackface sheep company	-28.2	2.8	46.9	14.8	3.7
GUsi5004	roe deer9	Blackface sheep company	-27.5	5.9	47.9	15.2	3.7
GUsi5005	roe deer10	Blackface sheep company	-26.6	3.6	46.8	14.7	3.7
GUsi5036	red deer1	Blackface sheep company	-26.3	4.0	46.4	14.7	3.7
GUsi5037	red deer2	Blackface sheep company	-26.1	3.2	46.6	14.7	3.7
GUsi5038	red deer3	Blackface sheep company	-25.9	5.2	45.7	14.5	3.7
GUsi5039	red deer4	Blackface sheep company	-26.6	4.9	45.8	14.1	3.8
GUsi5040	red deer5	Blackface sheep company	-26.4	3.8	45.8	14.4	3.7
GUsi5041	red deer6	Blackface sheep company	-26.0	4.5	45.6	14.3	3.7

Sample ID	Species	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi5042	red deer7	Blackface sheep company	-26.1	3.7	46.7	14.8	3.7
GUsi5043	red deer8	Blackface sheep company	-26.1	3.7	45.4	14.3	3.7
GUsi5044	red deer9	Blackface sheep company	-26.1	4.1	46.0	14.2	3.8
GUsi5045	red deer10	Blackface sheep company	-25.6	3.1	45.9	14.5	3.7
GUsi5046	Cattle1	Hugh Grierson	-26.5	5.0	40.6	12.9	3.7
GUsi5047	Cattle2	Hugh Grierson	-26.6	6.1	45.7	14.4	3.7
GUsi5048	Cattle3	Hugh Grierson	-26.8	5.8	46.8	14.8	3.7
GUsi5049	Sheep1	Hugh Grierson	-27.7	7.7	45.7	14.4	3.7
GUsi5050	Sheep2	Hugh Grierson	-27.7	7.4	45.2	14.2	3.7
GUsi5051	Sheep3	Hugh Grierson	-27.7	8.4	47.5	14.9	3.7
GUsi5052	Sheep4	Hugh Grierson	-27.8	7.2	46.5	14.6	3.7
GUsi5053	Sheep5	Hugh Grierson	-27.7	8.4	45.8	14.5	3.7
GUsi5054	Sheep6	Hugh Grierson	-27.9	8.4	46.1	14.6	3.7

5.3.2 Modern marine fish bone and muscle samples

The $\delta^{13}C$ measurements of the marine fish bone collagen including lipids ranged from -18.5 to -13.8‰ and μ = -16.1 ±1.4‰. The $\delta^{15}N$ measurements of the marine fish bone collagen including lipids ranged from 11.7 to 13.3‰ μ = 11.8 ± 1.7‰ The $\delta^{13}C$ measurements of the marine fish bone collagen ranged from -17.5 to -14.2‰ and μ = -15.2 ± 0.8‰. The $\delta^{15}N$ measurements of the marine fish bone collagen ranged from 11.7 to 13.9‰ μ = 11.8 ± 1.7‰.

The $\delta^{13}C$ measurements of the marine fish muscle samples including lipids ranged from -22.7 to -16.9‰ and μ = -19.0 ± 1.9‰. The $\delta^{15}N$ measurements of the marine fish muscle samples including lipids ranged from 9.2 to 14.6‰ and μ = 12.1 ± 1.8‰. The $\delta^{13}C$ measurements of the marine fish muscle ranged from -20.0 to -16.8‰ and μ = -17.9 ± 0.7‰.

The $\delta^{15}N$ measurements of the marine fish muscle ranged from 12.5 to 8.4‰ μ = 13.3 ±1.8‰.

Table 5.5 Stable carbon and nitrogen isotope values for samples of modern marine fish bone collagen including lipids from the North Sea, Scotland.

Sample ID	**Species and individual number**	**Site name**	**$\delta^{13}C$ ‰**	**$\delta^{15}N$ ‰**	**%C**	**%N**	**C/N atomic ratio**
GUsi4008	Haddock1	North sea	-15.3	11.7	39.6	13.7	3.4
GUsi4009	Haddock2	North sea	-15.0	12.6	39.8	13.7	3.4
GUsi4010	Haddock3	North sea	-14.6	13.2	38.5	13.6	3.3
GUsi4011	Haddock4	North sea	-14.5	11.7	39.0	13.7	3.3
GUsi4012	Haddock5	North sea	-14.4	12.8	41.2	14.5	3.3
GUsi4013	Haddock6	North sea	-14.2	13.3	39.0	14.0	3.3
GUsi4014	Haddock7	North sea	-14.9	12.0	37.0	13.0	3.3
GUsi4015	Haddock8	North sea	-14.3	11.8	39.6	14.1	3.3
GUsi4016	Haddock9	North sea	-13.8	13.1	39.5	14.1	3.3
GUsi4017	Haddock10	North sea	-13.9	11.8	38.1	13.9	3.2
GUsi4040	Cod1	North sea	-17.8	13.7	40.1	11.3	4.1
GUsi4041	Cod2	North sea	-16.0	13.2	36.6	11.5	3.7
GUsi4042	Cod3	North sea	-18.5	13.7	41.3	11.0	4.4
GUsi4043	Cod4	North sea	-18.0	12.2	36.6	10.7	4.0
GUsi4044	Cod5	North sea	-15.8	13.9	38.0	11.4	3.9
GUsi4045	Cod6	North sea	-17.4	13.4	41.4	11.5	4.2
GUsi4046	Cod7	North sea	-17.1	13.2	37.0	10.7	4.0
GUsi4047	Cod8	North sea	-18.1	13.2	40.2	10.9	4.3
GUsi4048	Cod9	North sea	-17.3	14.2	40.1	11.2	4.2
GUsi4049	Cod10	North sea	-17.9	13.1	34.0	9.9	4.0
GUsi4409	Pollock1	North sea	-15.5	9.6	36.7	12.4	3.5
GUsi4410	Pollock2	North sea	-17.9	9.0	35.3	11.9	3.4
GUsi4411	Pollock3	North sea	-16.4	9.2	38.9	13.3	3.4
GUsi4412	Pollock4	North sea	-16.1	10.0	42.9	14.1	3.5

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4413	Pollock5	North sea	-17.0	9.3	38.2	11.6	3.8
GUsi4414	Pollock6	North sea	-16.0	10.0	40.1	13.2	3.5
GUsi4415	Pollock7	North sea	-16.8	9.2	37.6	12.1	3.6
GUsi4416	Pollock8	North sea	-15.9	9.7	40.9	13.6	3.5
GUsi4417	Pollock9	North sea	-16.1	9.7	40.9	13.5	3.5
GUsi4418	Pollock10	North sea	-18.0	9.5	39.6	12.9	3.6

Table 5.6 Stable carbon and nitrogen isotope measurements for modern marine bone collagen samples from the North Sea, Scotland

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4020	Haddock1	North sea	-14.7	12.1	36.6	12.5	3.4
GUsi4021	Haddock2	North sea	-15.0	12.4	33.4	11.7	3.3
GUsi4022	Haddock3	North sea	-14.6	13.1	33.0	11.6	3.3
GUsi4023	Haddock4	North sea	-14.7	11.7	34.4	12.1	3.3
GUsi4024	Haddock5	North sea	-14.5	12.7	36.8	12.9	3.3
GUsi4025	Haddock6	North sea	-14.2	13.0	34.5	12.4	3.3
GUsi4026	Haddock7	North sea	-15.0	11.9	34.8	12.3	3.3
GUsi4027	Haddock8	North sea	-14.4	11.7	37.3	13.2	3.3
GUsi4028	Haddock9	North sea	-14.6	13.2	36.6	12.9	3.3
GUsi4029	Haddock10	North sea	-14.7	11.9	38.8	14.0	3.2
GUsi4332	Cod1	North sea	-15.6	13.6	36.2	12.9	3.3
GUsi4333	Cod2	North sea	-14.9	13.4	36.3	12.9	3.3
GUsi4334	Cod3	North sea	-15.1	13.8	35.6	12.9	3.2
GUsi4335	Cod4	North sea	-15.2	12.9	35.6	12.6	3.3
GUsi4336	Cod5	North sea	-14.2	13.8	36.3	12.8	3.3

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4337	Cod6	North sea	-14.7	13.1	35.1	11.9	3.5
GUsi4338	Cod7	North sea	-15.5	13.2	38.0	13.3	3.3
GUsi4339	Cod8	North sea	-15.0	12.9	34.1	12.0	3.3
GUsi4340	Cod9	North sea	-14.9	13.9	36.2	12.8	3.3
GUsi4341	Cod10	North sea	-16.2	12.9	34.5	11.8	3.4
GUsi4419	Pollock1	North sea	-15.0	9.9	40.3	14.2	3.3
GUsi4420	Pollock2	North sea	-17.2	9.0	40.4	14.1	3.3
GUsi4421	Pollock3	North sea	-15.7	9.0	37.9	13.5	3.3
GUsi4422	Pollock4	North sea	-15.0	9.9	39.1	13.8	3.3
GUsi4423	Pollock5	North sea	-15.6	9.5	39.2	13.8	3.3
GUsi4424	Pollock6	North sea	-15.4	10.1	36.1	12.5	3.4
GUsi4425	Pollock7	North sea	-16.0	9.3	39.6	13.8	3.3
GUsi4426	Pollock8	North sea	-15.4	9.9	39.9	13.9	3.3
GUsi4427	Pollock9	North sea	-15.9	9.8	39.3	13.4	3.4
GUsi4428	Pollock10	North sea	-17.5	9.3	38.8	13.4	3.4

Table 5.7 Stable carbon and nitrogen isotope values for samples of marine fish muscle including lipids from the North Sea, Scotland

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi3998	Haddock1	North Sea	-17.5	12.1	44.5	14.1	3.7
GUsi3999	Haddock2	North Sea	-17.5	13.1	44.5	14.0	3.7
GUsi4000	Haddock3	North Sea	-17.5	13.2	45.4	14.1	3.8
GUsi4001	Haddock4	North Sea	-17.5	12.6	44.5	13.9	3.7
GUsi4002	Haddock5	North Sea	-17.1	13.3	46.2	14.3	3.8
GUsi4003	Haddock6	North Sea	-17.3	13.4	45.1	14.1	3.7

Sample ID	Species and individual number	Site name	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi4004	Haddock7	North Sea	-17.7	12.5	44.2	13.9	3.7
GUsi4005	Haddock8	North Sea	-17.6	11.1	44.0	13.8	3.7
GUsi4006	Haddock9	North Sea	-16.9	13.9	44.7	13.9	3.8
GUsi4007	Haddock10	North Sea	-17.6	11.8	43.2	13.5	3.7
GUsi4050	Cod1	North Sea	-18.3	14.0	45.8	14.6	3.7
GUsi4051	Cod2	North Sea	-17.9	13.6	47.0	14.9	3.7
GUsi4052	Cod3	North Sea	-18.4	14.1	47.9	15.0	3.7
GUsi4053	Cod4	North Sea	-18.2	13.6	46.0	14.7	3.6
GUsi4054	Cod5	North Sea	-17.3	14.6	45.0	14.3	3.7
GUsi4055	Cod6	North Sea	-17.8	13.8	46.3	14.7	3.7
GUsi4056	Cod7	North Sea	-17.9	13.8	46.7	14.8	3.7
GUsi4057	Cod8	North Sea	-18.2	13.6	47.5	14.9	3.7
GUsi4058	Cod9	North Sea	-17.7	14.3	45.2	14.4	3.7
GUsi4059	Cod10	North Sea	-18.7	13.5	45.6	14.7	3.6
GUsi4429	Pollock1	North Sea	-20.9	10.2	56.5	10.2	6.5
GUsi4430	Pollock2	North Sea	-22.3	9.9	56.3	9.9	6.6
GUsi4431	Pollock3	North Sea	-22.5	9.2	53.5	8.4	7.4
GUsi4432	Pollock4	North Sea	-21.1	10.1	53.7	10.2	6.1
GUsi4433	Pollock5	North Sea	-22.1	9.2	56.0	9.7	6.7
GUsi4434	Pollock6	North Sea	-20.4	10.6	55.4	10.7	6.1
GUsi4435	Pollock7	North Sea	-21.8	9.4	56.9	10.3	6.4
GUsi4436	Pollock8	North Sea	-19.3	9.2	48.6	13.0	4.4
GUsi4437	Pollock9	North Sea	-21.6	9.7	54.5	7.8	8.1
GUsi4438	Pollock10	North Sea	-22.7	10.2	56.0	9.9	6.6

Table 5.8 Stable carbon and nitrogen isotope values for marine fish muscle samples from the North Sea, Scotland

Sample ID	Species and individual number	Site name	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi5006	Haddock1	North Sea	-17.4	13.4	46.9	15.0	3.6
GUsi5007	Haddock2	North Sea	-17.4	14.5	47.3	15.0	3.7
GUsi5008	Haddock3	North Sea	-17.4	14.6	46.7	14.9	3.7
GUsi5009	Haddock4	North Sea	-17.5	14.0	46.4	14.8	3.7
GUsi5010	Haddock5	North Sea	-17.1	14.8	46.8	14.9	3.7
GUsi5011	Haddock6	North Sea	-17.4	14.9	48.0	15.3	3.7
GUsi5012	Haddock7	North Sea	-17.7	13.7	47.1	15.0	3.7
GUsi5013	Haddock8	North Sea	-17.5	12.5	46.4	14.7	3.7
GUsi5014	Haddock9	North Sea	-16.8	15.3	47.3	14.9	3.7
GUsi5015	Haddock10	North Sea	-17.1	13.6	47.9	15.2	3.7
GUsi5016	Cod1	North Sea	-17.7	15.3	46.4	14.8	3.7
GUsi5017	Cod2	North Sea	-17.5	14.6	44.6	14.1	3.7
GUsi5018	Cod3	North Sea	-18.0	15.2	45.8	14.5	3.7
GUsi5019	Cod4	North Sea	-17.4	14.8	34.5	11.0	3.7
GUsi5020	Cod5	North Sea	-17.9	15.1	49.5	15.7	3.7
GUsi5021	Cod6	North Sea	-18.0	14.6	50.4	16.0	3.7
GUsi5022	Cod7	North Sea	-17.7	14.9	45.6	14.4	3.7
GUsi5023	Cod8	North Sea	-18.0	14.6	47.0	14.9	3.7
GUsi5024	Cod9	North Sea	-17.2	15.6	44.4	14.2	3.6
GUsi5025	Cod10	North Sea	-18.3	14.9	44.6	14.2	3.7
GUsi5026	Pollock1	North Sea	-18.0	11.5	46.5	14.2	3.8
GUsi5027	Pollock2	North Sea	-19.6	11.1	46.3	14.3	3.8
GUsi5028	Pollock3	North Sea	-18.7	10.3	46.6	14.2	3.8
GUsi5029	Pollock4	North Sea	-18.2	11.3	46.3	14.2	3.8
GUsi5030	Pollock5	North Sea	-18.9	10.7	46.7	14.3	3.8
GUsi5031	Pollock6	North Sea	-17.9	11.7	47.2	14.5	3.8
GUsi5032	Pollock7	North Sea	-18.8	10.7	46.2	14.2	3.8

Sample ID	Species and individual number	Site name	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C/N atomic ratio
GUsi5033	Pollock8	North Sea	-17.5	10.1	46.1	14.4	3.7
GUsi5034	Pollock9	North Sea	-18.2	11.1	45.7	14.1	3.8
GUsi5035	Pollock10	North Sea	-20.0	11.2	46.7	14.2	3.8

5.3.3 Modern shellfish muscle samples

The $\delta^{13}C$ measurements of all marine shellfish muscle samples including lipids ranged from -19.6 to -13.5‰ and μ = -16.7 ± 1.3‰. The $\delta^{15}N$ measurements of all terrestrial muscle samples including lipids ranged from 6.2 to 12.0‰ and μ = 8.7 ±1.5‰. The $\delta^{13}C$ measurements of all marine shellfish muscle ranged from -18.1 to -12.4‰ and μ = -16.0 ±1.0‰. The $\delta^{15}N$ measurements of all marine shellfish muscle ranged from 6.3 to 12.1‰ μ = 9.2 ± 1.3‰.

Table 5.9 Stable carbon and nitrogen isotope values for samples of limpet muscle including lipids from Airds Bay, SAMS, Papa Westray, Grobust Bay and Pool, Scotland

Sample ID	Site name and individual number	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C/N atomic ratio
GUsi3201	Airds Bay1	-15.8	6.3	37.4	10.7	4.1
GUsi3202	Airds Bay2	-17.2	6.7	33	8.5	4.5
GUsi3203	Airds Bay3	-16.4	6.3	38.8	10.7	4.2
GUsi3204	Airds Bay4	-16.4	6.3	38.4	10.8	4.1
GUsi3205	Airds Bay5	-16.4	7.1	37.6	11.6	3.8
GUsi3206	Airds Bay6	-15.8	7.0	38.6	11.4	4.0
GUsi3207	Airds Bay7	-16.5	6.7	35.2	10.7	3.8
GUsi3251	SAMS1	-15.5	7.8	40.1	11.8	4.0
GUsi3216	SAMS2	-17.3	6.9	36.5	10.6	4.0

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3217	SAMS3	-16.9	6.2	37	9.4	4.6
GUsi3218	SAMS4	-17.2	7.8	40.1	10.4	4.5
GUsi3219	SAMS5	-16.8	8.8	37.7	9.9	4.4
GUsi3220	SAMS6	-18.1	5.8	38.7	8.9	5.1
GUsi3227	Papa Westray1	-19.6	7.5	42.8	8.1	6.2
GUsi3228	Papa Westray2	-19.6	7.5	43.9	7.8	6.5
GUsi3229	Papa Westray3	-18.7	7.0	41.9	10.0	4.9
GUsi3265	Papa Westray4	-18.0	6.5	41.5	11.1	4.4
GUsi3266	Papa Westray5	-16.3	7.4	41.4	10.9	4.4
GUsi3267	Papa Westray6	-16.6	8.0	39.9	12.0	3.9
GUsi3268	Papa Westray7	-15.9	8.4	41.0	10.2	4.7
GUsi3269	Papa Westray8	-16.8	6.5	38.9	10.8	4.2
GUsi3270	Papa Westray9	-17.0	7.6	39.3	10.0	4.6
GUsi3233	Papa Westray10	-17.5	8.2	38.2	9.4	4.7
GUsi3234	Papa Westray11	-15.6	8.2	37.4	10.3	4.2
GUsi3235	Papa Westray12	-18.4	7.6	40.4	9.4	5.0
GUsi3271	Papa Westray13	-15.2	8.0	36.7	11.2	3.8
GUsi3272	Papa Westray14	-17.2	8.6	39.5	10.3	4.5
GUsi3273	Papa Westray15	-17.7	8.6	39.8	10.7	4.4
GUsi3274	Papa Westray16	-15.5	7.6	38.5	10.4	4.3
GUsi3275	Grobust Bay1	-17.6	6.9	38.3	10.8	4.1
GUsi3276	Grobust Bay2	-17.0	9.3	38.7	9.3	4.9
GUsi3277	Grobust Bay3	-17.7	6.8	39.3	9.2	5.0
GUsi3278	Grobust Bay4	-18.2	7.6	38.9	9.7	4.7
GUsi3279	Grobust Bay5	-17.0	7.4	40.9	10.5	4.6
GUsi3280	Grobust Bay6	-17.1	7.5	38.7	9.9	4.6
GUsi3281	Grobust Bay7	-17.4	9.0	34.5	10.4	3.9
GUsi3282	Grobust Bay8	-16.5	7.5	37.0	11.0	3.9
GUsi3283	Grobust Bay9	-17.7	7.4	35.8	10.0	4.2
GUsi3284	Grobust Bay10	-17.3	7.1	37.3	11.3	3.9

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3285	Pool1	-17.4	7.6	41.5	10.1	4.8
GUsi3286	Pool2	-17.0	7.9	37.7	11.1	4.0
GUsi3287	Pool3	-13.4	7.1	37.8	9.0	4.9
GUsi3288	Pool4	-17.5	8.3	41.1	9.8	4.9
GUsi3289	Pool5	-15.5	7.6	42.7	10.3	4.8
GUsi3290	Pool6	-16.8	7.6	44.1	9.7	5.3

Table 5.10 Stable carbon and nitrogen isotope values for limpet muscle samples from Airds Bay, SAMS, Papa Westray, Grobust Bay and Pool, Scotland.

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3208	Airds Bay1	-14.9	7.0	44.2	14.2	3.6
GUsi3209	Airds Bay2	-15.8	7.4	38.5	12.4	3.6
GUsi3210	Airds Bay3	-15.8	6.3	42.4	12.9	3.8
GUsi3211	Airds Bay4	-15.9	6.7	42.7	13.8	3.6
GUsi3212	Airds Bay5	-15.8	7.8	43.7	14.6	3.5
GUsi3213	Airds Bay6	-14.8	7.2	43.0	13.9	3.6
GUsi3214	Airds Bay7	-16.0	7.0	41.3	13.7	3.5
GUsi3221	SAMS1	-14.4	8.4	42.6	13.6	3.6
GUsi3222	SAMS2	-16.3	8.0	42.2	14.1	3.5
GUsi3223	SAMS3	-15.5	7.5	43.8	14.1	3.6
GUsi3224	SAMS4	-15.8	9.1	44.4	13.8	3.7
GUsi3225	SAMS5	-15.6	9.8	44.3	13.9	3.7
GUsi3226	SAMS6	-16.0	6.7	43.3	12.8	3.9
GUsi3230	Papa Westray1	-16.9	8.4	41.9	12.8	3.8
GUsi3231	Papa Westray2	-16.8	8.5	41.3	12.1	4.0
GUsi3232	Papa Westray3	-17.3	8.2	44.8	13.9	3.7
GUsi3354	Papa Westray4	-16.8	7.6	48.6	15.9	3.6

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3355	Papa Westray5	-15.8	7.9	46.0	13.2	4.1
GUsi3356	Papa Westray6	-15.4	8.3	46.4	15.6	3.5
GUsi3357	Papa Westray7	-15.1	8.8	46.3	13.5	4.0
GUsi3358	Papa Westray8	-16.3	6.6	44.7	14.2	3.7
GUsi3359	Papa Westray9	-16.6	8.1	44.8	11.2	4.7
GUsi3236	Papa Westray10	-16.3	8.9	43.7	14.0	3.6
GUsi3237	Papa Westray11	-14.8	8.8	42.6	13.7	3.6
GUsi3238	Papa Westray12	-16.6	8.8	43.9	12.6	4.0
GUsi3360	Papa Westray13	-14.6	8.3	45.6	15.2	3.5
GUsi3361	Papa Westray15	-16.6	9.4	45.5	14.0	3.8
GUsi3362	Papa Westray15	-16.7	9.6	44.5	13.7	3.8
GUsi3363	Papa Westray16	-14.8	8.6	45.9	13.3	4.0
GUsi3364	Grobust Bay1	-16.5	7.7	45.9	14.9	3.6
GUsi3365	Grobust Bay2	-15.6	9.6	44.5	14.2	3.7
GUsi3366	Grobust Bay3	-16.5	8.0	45.8	13.3	4.0
GUsi3367	Grobust Bay4	-17.8	7.8	45.3	12.5	4.2
GUsi3368	Grobust Bay5	-16.3	7.4	44.7	12.9	4.0
GUsi3369	Grobust Bay6	-16.0	8.1	45.3	14.1	3.7
GUsi3370	Grobust Bay7	-16.5	9.6	46.2	15.2	3.5
GUsi3371	Grobust Bay8	-15.7	8.2	45.2	14.7	3.6
GUsi3372	Grobust Bay9	-17.0	8.1	45.3	14.5	3.6
GUsi3373	Grobust Bay10	-16.8	7.8	45.5	14.9	3.6
GUsi3374	Pool1	-16.5	8.2	44.9	12.7	4.1
GUsi3375	Pool2	-16.3	8.9	46.4	15.0	3.6
GUsi3376	Pool3	-12.8	7.5	44.7	11.9	4.4
GUsi3377	Pool4	-16.6	8.7	46.5	13.8	3.9
GUsi3378	Pool5	-15.1	7.8	46.5	13.3	4.1
GUsi3379	Pool6	-16.2	8.5	46.0	13.1	4.1

Table 5.11 Stable carbon and nitrogen isotope values for samples of mussel muscle including lipids from Airds Bay, Papa Westray and Pool, Scotland

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/Natomic ratio
GUsi3173	Airds Bay1	-18.9	8.8	38.7	9.9	4.5
GUsi3174	Airds Bay2	-18.1	8.8	36.4	10.2	4.2
GUsi3175	Airds Bay3	-18.3	8.5	34.9	9.7	4.2
GUsi3176	Airds Bay4	-18.1	8.6	33.5	9.4	4.1
GUsi3177	Airds Bay5	-19.5	8.4	41.8	9.5	5.1
GUsi3178	Airds Bay6	-18.3	8.4	35.1	9.9	4.1
GUsi3179	Airds Bay7	-17.3	9.1	35.3	10.5	3.9
GUsi3180	Airds Bay8	-18.8	8.7	39.4	10.9	4.2
GUsi3189	Papa Westray1	-18.2	7.3	38.2	9.6	4.6
GUsi3190	Papa Westray2	-17.5	10.1	38.1	9.7	4.6
GUsi3191	Papa Westray3	-18.3	7.6	36.5	9.3	4.6
GUsi3192	Papa Westray4	-17.6	7.5	38.3	11.5	3.9
GUsi3193	Papa Westray5	-19.3	6.5	39.6	8.8	5.2
GUsi3194	Papa Westray6	-18.1	8.0	35.4	8.9	4.7
GUsi3262	Papa Westray7	-18.0	7.1	36.3	9.4	4.5
GUsi3263	Papa Westray8	-18.3	7.8	37.3	8.8	4.9
GUsi3264	Papa Westray9	-16.9	7.7	38.9	10.2	4.5
GUsi3424	Pool1	-15.7	8.2	35.7	9.9	4.2

Table 5.12 Stable carbon and nitrogen isotope values for mussel muscle samples from Airds Bay and Papa Westray, Scotland

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/Natomic ratio
GUsi3181	Airds Bay1	-16.7	9.5	42.8	13.8	3.6
GUsi3182	Airds Bay2	-16.4	9.1	44	14.5	3.5
GUsi3183	Airds Bay3	-17.1	9.1	43.5	14.5	3.5
GUsi3184	Airds Bay4	-16.7	9.4	43.3	14.4	3.5
GUsi3185	Airds Bay5	-17.1	9.4	43.8	13.8	3.7
GUsi3186	Airds Bay6	-16.9	9.3	43.7	14.5	3.5
GUsi3187	Airds Bay7	-16.7	9.3	43	14.5	3.4
GUsi3188	Airds Bay8	-17.5	8.8	43.4	14.5	3.5
GUsi3195	Papa Westray1	-16.9	8.8	45.6	15.0	3.5
GUsi3196	Papa Westray2	-16.7	10.8	44.1	14.4	3.6
GUsi3197	Papa Westray3	-17.1	8.4	45.6	15.3	3.5
GUsi3198	Papa Westray4	-16.7	8.2	44.7	15.2	3.4
GUsi3199	Papa Westray5	-17.5	8.4	44.8	14.4	3.6
GUsi3200	Papa Westray6	-16.4	8.8	45.1	14.4	3.6
GUsi3351	Papa Westray7	-17.2	8.1	44.7	13.5	3.8
GUsi3352	Papa Westray8	-17.1	8.6	43.8	13.0	3.9
GUsi3353	Papa Westray9	-16.4	7.8	41.5	11.9	4.1

Table 5.13 Stable carbon and nitrogen isotope values for samples of cockle muscle including lipids from Airds Bay and SAMS, Scotland

Sample ID	**Site name and individual number**	**$\delta^{13}C‰$**	**$\delta^{15}N‰$**	**%C**	**%N**	**C/Natomic ratio**
GUsi3425	Airds Bay1	-18.2	9.2	33.3	9.0	4.3
GUsi3426	Airds Bay2	-18.2	9.0	38.3	10.2	4.4
GUsi3427	Airds Bay3	-18.9	8.4	34.7	9.0	4.5
GUsi3428	SAMS1	-17.8	9.9	35.9	8.5	4.9
GUsi3429	SAMS2	-16.8	9.6	33.7	9.1	4.3
GUsi3430	SAMS3	-17.8	9.7	37.5	9.9	4.4
GUsi3431	SAMS4	-17.0	10.3	31.7	8.1	4.6
GUsi3432	SAMS5	-17.8	9.5	35.7	9.6	4.3
GUsi3433	SAMS6	-18.1	9.2	36.0	9.2	4.5
GUsi3434	SAMS7	-17.6	9.3	38.3	10.6	4.2
GUsi3435	SAMS8	-17.8	9.5	35.0	8.9	4.6

Table 5.14 Stable carbon and nitrogen isotope values for cockle muscle samples from Airds Bay and SAMS, Scotland

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3533	Airds Bay1	-17.1	10.0	45.7	14.6	3.6
GUsi3534	Airds Bay2	-17.4	9.4	44.1	13.6	3.8
GUsi3535	Airds Bay3	-18.1	9.5	48.0	15.1	3.7
GUsi3536	SAMS1	-17.3	9.8	44.0	11.4	4.5
GUsi3537	SAMS2	-16.4	8.6	42.0	13.4	3.7
GUsi3538	SAMS3	-17.2	9.6	47.4	12.8	4.3
GUsi3539	SAMS4	-16.0	10.3	45.1	14.3	3.7
GUsi3540	SAMS5	-17.2	9.7	45.5	12.5	4.2
GUsi3541	SAMS6	-17.0	9.4	46.7	14.6	3.7
GUsi3542	SAMS7	-16.9	9.6	44.9	13.9	3.8
GUsi3543	SAMS8	-17.1	9.7	45.2	12.9	4.1

Table 5.15 Stable carbon and nitrogen isotope values for samples of winkle muscle including lipids from Airds Bay, SAMS, Papa Westray, Grobust Bay and Pool, Scotland

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/Natomic ratio
GUsi3436	Airds Bay1	-16.0	9.7	38.6	11.4	4.0
GUsi3437	Airds Bay2	-16.2	9.3	39.1	11.1	4.1
GUsi3438	Airds Bay3	-16.6	9.0	38.5	10.9	4.1
GUsi3439	Airds Bay4	-16.0	9.2	39.0	11.3	4.0
GUsi3440	Airds Bay5	-15.7	9.0	39.4	11.1	4.1
GUsi3441	Airds Bay6	-16.2	9.2	38.9	11.1	4.1
GUsi3442	Airds Bay7	-15.0	9.0	39.1	11.7	3.9
GUsi3443	SAMS1	-15.4	8.4	38.9	9.6	4.7
GUsi3444	SAMS2	-15.6	8.1	40.0	11.2	4.2
GUsi3445	SAMS3	-16.9	11.9	37.2	9.9	4.4
GUsi3446	SAMS4	-16.6	11.7	39.9	11.5	4.0
GUsi3447	SAMS5	-15.7	8.0	38.8	11.1	4.1
GUsi3448	SAMS6	-15.7	11.7	39.5	11.7	3.9
GUsi3449	SAMS7	-16.8	11.0	39.3	9.2	5.0
GUsi3450	SAMS8	-16.3	12.0	38.4	9.8	4.6
GUsi3451	SAMS9	-14.8	8.5	38.4	11.7	3.8
GUsi3452	Papa Westray1	-15.9	10.9	37.6	10.6	4.1
GUsi3453	Papa Westray2	-16.7	10.5	38.3	10.7	4.2
GUsi3454	Papa Westray3	-16.6	10.5	37.9	10.3	4.3
GUsi3455	Papa Westray4	-16.7	10.3	38.3	10.3	4.3
GUsi3456	Papa Westray5	-16.0	10.1	40.3	11.9	3.9
GUsi3457	Papa Westray6	-16.2	11.0	38.1	11.1	4.0
GUsi3458	Papa Westray7	-16.4	10.6	35.3	9.6	4.3
GUsi3459	Papa Westray8	-15.9	10.9	40.0	11.6	4.0
GUsi3460	Papa Westray9	-16.6	10.4	39.3	10.9	4.2
GUsi3571	Papa Westray10	-14.0	9.8	40.1	11.1	4.2
GUsi3572	Papa Westray11	-16.0	10.7	39.7	11.6	4.0
GUsi3573	Papa Westray12	-15.7	9.3	38.5	7.8	5.8
GUsi3574	Papa Westray13	-15.9	10.6	40.3	11.3	4.2

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/Natomic ratio
GUsi3575	Papa Westray14	-15.5	10.7	38.0	10.1	4.4
GUsi3576	Papa Westray15	-16.2	11.1	41.1	11.1	4.3
GUsi3577	Papa Westray16	-16.3	10.8	38.1	10.3	4.3
GUsi3578	Papa Westray17	-15.9	10.3	39.7	9.9	4.7
GUsi3579	Papa Westray18	-16.1	11.1	37.5	9.0	4.9
GUsi3580	Papa Westray19	-15.3	10.5	38.2	10.7	4.2
GUsi3581	Grobust Bay1	-17.1	10.5	38.9	8.1	5.6
GUsi3582	Grobust Bay2	-17.0	11.0	39.8	11.3	4.1
GUsi3583	Grobust Bay3	-16.8	10.5	35.2	9.2	4.5
GUsi3584	Pool1	-13.5	8.5	37.9	11.0	4.0
GUsi3585	Pool2	-13.7	7.0	36.6	8.3	5.1
GUsi3586	Pool3	-16.0	10.3	41.4	11.3	4.3
GUsi3587	Pool4	-14.8	10.0	38.1	10.0	4.4
GUsi3588	Pool5	-14.5	8.4	35.9	10.6	3.9
GUsi3589	Pool6	-13.0	7.6	37.7	9.9	4.4
GUsi3590	Pool7	-14.5	10.0	37.1	9.0	4.8
GUsi3591	Pool8	-15.9	10.2	39.8	10.8	4.3
GUsi3592	Pool9	-14.2	10.2	40.0	10.8	4.3
GUsi3593	Pool10	-14.1	10.0	36.6	9.1	4.7

Table 5.16 Stable carbon and nitrogen isotope values for winkle muscle samples from Airds Bay, SAMS, Papa Westray, Grobust Bay and Pool, Scotland

Sample ID	Site name and individual number	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3544	Airds Bay1	-15.1	10.2	42.4	13.4	3.7
GUsi3545	Airds Bay2	-15.5	9.6	40.5	12.1	3.9
GUsi3546	Airds Bay3	-15.7	9.3	44.4	13.8	3.7
GUsi3547	Airds Bay4	-15.3	9.6	45.0	13.9	3.8
GUsi3548	Airds Bay5	-14.7	9.7	46.2	14.4	3.8
GUsi3549	Airds Bay6	-15.7	10.0	46.3	14.4	3.7
GUsi3594	Airds Bay7	-14.9	9.7	45.1	14.2	3.7
GUsi3595	SAMS1	-14.4	8.7	43.9	13.5	3.8
GUsi3596	SAMS2	-15.5	8.4	45.8	14.3	3.7
GUsi3565	SAMS3	-15.7	11.7	45.7	14.6	3.7
GUsi3598	SAMS4	-16.1	11.8	46.5	14.9	3.6
GUsi3599	SAMS5	-15.3	8.8	45.0	13.5	3.9
GUsi3600	SAMS6	-15.6	9.6	45.3	14.1	3.7
GUsi3601	SAMS7	-15.8	11.6	44.4	13.6	3.8
GUsi3602	SAMS8	-16.1	12.1	45.2	13.9	3.8
GUsi3603	SAMS9	-14.1	9.0	45.2	14.6	3.6
GUsi3604	Papa Westray1	-15.8	10.4	44.6	14.5	3.6
GUsi3605	Papa Westray2	-16.4	10.7	45.3	14.0	3.8
GUsi3606	Papa Westray3	-16.3	10.8	46.2	13.8	3.9
GUsi3607	Papa Westray4	-16.7	11.0	46.9	14.4	3.8
GUsi3608	Papa Westray5	-15.9	10.8	44.8	11.4	4.6
GUsi3609	Papa Westray6	-16.3	10.6	45.7	14.1	3.8
GUsi3634	Papa Westray7	-16.3	10.3	45.0	14.2	3.7
GUsi3635	Papa Westray8	-16.2	10.7	45.4	14.1	3.8
GUsi3636	Papa Westray9	-16.8	10.6	44.3	12.5	4.1
GUsi3637	Papa Westray10	-13.7	10.0	45.66	14.10	3.8
GUsi3638	Papa Westray11	-15.8	11.2	46.25	14.75	3.7
GUsi3639	Papa Westray12	-15.4	10.6	46.92	14.22	3.8

Sample ID	Site name and individual number	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C/N atomic ratio
GUsi3640	Papa Westray13	-15.9	11.0	46.23	14.48	3.7
GUsi3641	Papa Westray14	-15.5	11.2	44.41	12.77	4.1
GUsi3642	Papa Westray15	-15.9	11.3	43.57	10.54	4.8
GUsi3643	Papa Westray16	-15.6	11.6	45.46	14.54	3.6
GUsi3644	Papa Westray17	-15.9	10.8	44.29	13.34	3.9
GUsi3645	Papa Westray18	-15.8	11.1	43.17	13.23	3.8
GUsi3646	Papa Westray19	-16.1	11.0	44.28	12.72	4.1
GUsi3647	Grobust Bay1	-16.7	10.9	43.83	12.36	4.1
GUsi3648	Grobust Bay2	-16.6	10.7	45.01	13.73	3.8
GUsi3649	Grobust Bay3	-16.3	10.7	45.2	13.9	3.8
GUsi3650	Pool1	-13.3	8.7	42.7	13.0	3.8
GUsi3651	Pool2	-12.4	7.2	42.3	12.8	3.9
GUsi3652	Pool3	-16.2	10.8	43.9	11.5	4.5
GUsi3653	Pool4	-14.9	10.4	43.2	12.1	4.2
GUsi3654	Pool5	-14.3	9.4	43.9	14.1	3.6
GUsi3655	Pool6	-12.7	7.8	43.4	12.1	4.2
GUsi3656	Pool7	-13.7	10.3	43.0	12.4	4.0
GUsi3657	Pool8	-15.3	11.3	44.9	13.4	3.9
GUsi3658	Pool9	-15.8	11.2	44.7	13.2	3.9
GUsi3659	Pool11	-13.5	10.3	43.9	13.0	3.9

5.3.4 Modern marine mammal bone samples

The $\delta^{13}C$ measurements of all marine mammal bone collagen samples ranged from -14.7 to -12.8‰ and μ = -13.9 ± 0.8‰. The $\delta^{15}N$ measurements of all marine mammal bone collagen samples ranged from 15.3 to 15.8‰ and μ = 15.6 ±0.2‰ (see Table 5.17).

Table 5.17 Stable carbon and nitrogen isotope values for marine mammal bone collagen samples from Sanday and Kirkwall, Scotland

Sample ID	**Site name**	**Species**	**$\delta^{13}C‰$**	**$\delta^{15}N‰$**	**%C**	**%N**	**C/N atomic ratio**
GUsi4675	Sanday	seal	-14.7	15.3	36.5	13.1	3.2
GUsi4676	Sanday	otter	-12.8	15.6	37.5	13.6	3.2
GUsi4677	Kirkwall	sperm whale	-14.3	15.8	29.5	10.4	3.3

5.3.5 Summary values for all modern marine and terrestrial isotope samples

Table 5.18 Mean stable carbon isotope values for modern terrestrial herbivores and marine fish bone collagen fractions from all sites in Scotland

Species	N individuals	bone collagen	1σ	Σ	bone collagen inc. lipids	1σ	Σ
Cattle	3	-24.9	0.2	0.1	-24.7	0.0	0.0
Sheep	6	-25.6	0.5	0.2	-25.5	0.2	0.1
Red deer	10	-24.5	0.3	0.1	-24.4	0.3	0.1
Roe deer	9	-24.9	0.6	0.2	-24.7	1.0	0.3
TERRESTRIAL	28	-24.9	0.6	0.1	-24.8	0.7	0.1
Cod	10	-15.1	0.5	0.2	-17.4	0.8	0.3
Pollock	10	-15.9	0.8	0.3	-16.6	0.8	0.3
Haddock	10	-14.6	0.2	0.1	-14.5	0.4	0.1
MARINE	30	-15.2	0.8	0.1	-16.1	1.4	0.3

Table 5.19 Mean stable nitrogen isotope values for modern terrestrial herbivores and marine fish bone collagen fractions from all sites in Scotland

Species	N individuals	bone collagen	1σ	Σ	bone collagen inc. lipids	1σ	Σ
Cattle	3	6.4	0.7	0.4	6.2	0.1	0.1
Sheep	6	7.3	0.7	0.3	7.6	0.5	0.1
Red deer	10	3.4	0.8	0.2	3.6	0.7	0.2
Roe deer	9	4.9	1.1	0.4	4.8	1.4	0.5
TERRESTRIAL	28	5.2	1.7	0.3	5.2	1.8	0.3
Cod	10	13.4	0.4	0.1	13.4	0.5	0.2
Pollock	10	9.6	0.4	0.1	9.5	0.3	0.1
Haddock	10	12.4	0.6	0.2	12.4	0.6	0.2
MARINE	30	11.8	1.7	0.3	11.8	1.7	0.3

Table 5.20 Mean stable carbon isotope values for modern terrestrial herbivores, shellfish and marine fish flesh fractions from all sites in Scotland

Species	**N individuals**	**muscle**	**1σ**	**Σ**	**Muscle inc. lipids**	**1σ**	**Σ**
Cattle	3	-26.6	0.1	0.1	-27.3	0.2	0.1
Sheep	6	-27.8	0.1	0.0	-29.5	0.7	0.3
Red deer	10	-26.1	0.3	0.1	-26.8	0.2	0.1
Roe deer	10	-27.1	0.5	0.2	-28.0	0.5	0.2
TERRESTRIAL	29	-26.8	0.7	0.1	-27.8	1.1	0.2
Cod	10	-17.8	0.3	0.1	-18.0	0.4	0.1
Pollock	10	-18.6	0.7	0.2	-21.5	1.0	0.3
Haddock	10	-17.3	0.2	0.1	-17.4	0.2	0.1
MARINE FISH	30	-17.9	0.7	0.1	-19.0	1.9	0.3
Limpet	45	-16.0	1.0	0.1	-17.0	1.1	0.2
Mussel	18	-16.9	0.3	0.1	-18.2	0.7	0.2
Cockle	11	-17.1	0.5	0.2	-17.8	0.5	0.2
Winkle	48	-15.4	1.0	0.1	-15.7	1.0	0.1
SHELLFISH	122	-16.0	1.0	0.1	-16.7	1.3	0.1

Table 5.21 Mean stable nitrogen isotope values for modern terrestrial herbivores, shellfish and marine fish flesh fractions from Scotland

Species	N individuals	muscle	1σ	Σ	Muscle inc. lipids	1σ	Σ
Cattle	3	5.6	0.5	0.3	5.4	0.6	0.3
Sheep	6	7.9	0.5	0.2	7.7	0.5	0.2
Red deer	10	4.0	0.6	0.2	3.7	0.6	0.2
Roe deer	10	5.6	1.7	0.5	5.5	1.3	0.4
TERRESTRIAL	29	5.4	1.7	0.3	5.4	1.7	0.3
Cod	10	15.0	0.3	0.1	13.9	0.3	0.1
Pollock	10	11.0	0.5	0.2	9.8	0.5	0.2
Haddock	10	14.1	0.8	0.3	12.7	0.8	0.3
MARINE	30	13.3	1.8	0.3	12.1	1.8	0.3
Limpet	45	8.1	0.8	0.1	7.5	0.8	0.1
Mussel	18	8.9	0.7	0.2	8.2	0.8	0.2
Cockle	11	9.6	0.4	0.1	9.4	0.5	0.1
Winkle	48	10.3	1.0	0.2	10.0	1.1	0.2
SHELLFISH	122	9.2	1.3	0.1	8.7	1.5	0.1

5.3.6 Stable carbon and nitrogen isotope tissue offsets for marine and terrestrial fauna

Muscle protein and bone collagen isotope values for modern marine fish and terrestrial mammal samples were used to calculate tissue isotope offset values. Faunal bone collagen mean isotope values were converted using $\Delta^{13}C_{\text{muscle protein- bone collagen}}$ offset values to derive FRUITS food values for each site (see Table 5.32 for a summary of these food values). For both marine fish and terrestrial herbivores, all tissue factions and all possible tissue offset values are presented to demonstrate isotopic differences in tissues with and without lipids. These various tissue offset values presented in here could be used in future dietary reconstruction research to calculate custom tissue offsets where the original isotope measurement is derived from either fresh bone or flesh.

Table 5.22 Stable carbon isotope tissue offsets for modern terrestrial herbivores and marine fish from Scotland

Species	N sample pairs	$\Delta^{13}C_{protein\text{-}collagen}$ inc. lipids (‰ ± 1σ)	$\Delta^{13}C$ protein-collagen (‰ ± 1σ)	$\Delta^{13}C_{collagen\ inc.}$ lipids-collagen (‰ ± 1σ)
Cattle	3	-2.0±0.1	-1.7±0.1	0.3±0.2
Sheep	6	-2.2±0.2	-2.2±0.6	0.1±0.6
Red deer	10	-1.7±0.3	-1.6±0.4	0.1±0.4
Roe deer	9	-2.4±0.8	-2.3±0.2	0.2±0.7
TERRESTRIAL	28	-2.1±0.6	-1.9±0.5	0.2±0.5
Cod	10	-0.4±0.8	-2.6±0.5	-2.2±0.7
Pollock	10	-2.0±0.2	-2.7±0.4	-0.7±0.3
Haddock	10	-2.8±0.3	-2.7±0.3	0.1±0.4
MARINE	30	-1.7±1.1	-2.7±0.4	-0.9±1.1

Table 5.23 Stable nitrogen isotope tissue offsets for modern terrestrial herbivores and marine fish from Scotland

Species	N sample pairs	$\Delta^{15}N_{protein\text{-}collagen}$ inc. lipids (‰ ± 1σ)	$\Delta^{15}N_{protein\text{-}}$ collagen (‰ ± 1σ)	$\Delta^{15}N_{collagen\text{-}bone}$ collagen inc. lipids (‰ ± 1σ)
Cattle	3	-0.8±0.5	-0.9±0.2	+0.2±0.7
Sheep	6	+0.1±0.9	+0.4±1.0	-0.3±0.8
Red deer	10	+0.1±0.6	+0.3±0.7	-0.2±0.2
Roe deer	9	+0.6±1.0	+0.5±0.5	+0.1±0.8
TERRESTRIAL	28	+0.2±0.9	+0.3±0.8	-0.1±0.7
Cod	10	+0.5±0.3	+0.5±0.2	0.0±0.4
Pollock	10	+0.3±0.4	+0.2±0.5	+0.1±0.2
Haddock	10	+0.3±0.4	+0.3±0.5	0.0±0.2
MARINE	30	+0.4±0.4	+0.4±0.4	0.0±0.2

5.4 Archaeological samples

5.4.1 Stable carbon and nitrogen isotope measurements of archaeological humans and fauna

The stable carbon and nitrogen isotope results from archaeological samples are presented in this section. Stable carbon and nitrogen isotope values and radiocarbon measurements of all Mesolithic and Neolithic human bone collagen samples examined in this research are introduced (Table 5.24). The results from the stable carbon and nitrogen isotope analysis of terrestrial herbivores from the archaeological fauna are categorised by site (Tables 5.25 to 5.29). The $\delta^{13}C$ measurements of the human bone collagen samples ranged from -22.4 to -12.0‰ and μ = -19.7 ± 3.3‰. The $\delta^{15}N$ measurements of the human bone collagen samples ranged from 7.7 to 17.0‰ and μ = 10.8 ± 2.5‰. The $\delta^{13}C$ measurements of the archaeological faunal bone collagen samples ranged from -24.5 to -20.1‰ and μ = -22.0 ± 0.8‰. The $\delta^{15}N$ measurements of the archaeological faunal bone collagen samples ranged from 0.8 to 9.5‰ and μ = 4.6 ± 1.9‰.

Table 5.24 Stable carbon and nitrogen isotope values of Mesolithic and Neolithic humans from all Scottish sites, including AMS radiocarbon ages

Sample ID	**Site name**	**Context**	**$\delta^{13}C$ ‰**	**$\delta^{15}N$ ‰**	**%C**	**%N**	**C/N atomic ratio**	**^{14}C Age (^{14}C yrs BP±1σ)**
OxA7663	Carding Mill Bay	C XIV:1	-21.5	9.0	N/A	N/A	3.2	4800±50
OxA7664	Carding Mill Bay	C XV:1	-21.0	8.9	N/A	N/A	3.1	4830±45
OxA7665	Carding Mill Bay	C VII:130	-21.5	9.6	N/A	N/A	3.2	4690±40
OxA7890	Carding Mill Bay	C XXIII	-21.4	9.8	N/A	N/A	3.1	4330±60
C III:74	Carding Mill Bay	C III:74	-21.3	8.8	N/A	N/A	3.2	N/A

Sample ID	Site name	Context	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio	^{14}C Age (^{14}C yrs BP±1σ)
C IV:94	Carding Mill Bay	C IV:94	-21.5	10.0	N/A	N/A	3.1	N/A
C V:105	Carding Mill Bay	C V:105	-21.3	8.9	N/A	N/A	3.2	N/A
C VII:112	Carding Mill Bay	C VII:112	-21.3	9.1	N/A	N/A	3.2	N/A
C X:1	Carding Mill Bay	C X:1	-21.3	9.5	N/A	N/A	3.1	N/A
C XVII:1	Carding Mill Bay	C XVII:1	-21.9	9.9	N/A	N/A	3.1	N/A
GU41836	Cnoc Coig	N/A	-12.8	16.6	N/A	N/A	3.3	5492±36
GU40827	Cnoc Coig	N/A	-13.1	16.1	32.3	11.2	3.4	5619±31
18104	Cnoc Coig	N/A	-13.2	14.5	N/A	N/A	3.1	N/A
OxA8019	Cnoc Coig	N/A	-12.3	16.0	N/A	N/A	3.1	5615±45
OxA8014	Cnoc Coig	N/A	-12.0	14.7	N/A	N/A	2.9	5495±55
OxA8004	Cnoc Coig	N/A	-12.0	17.0	N/A	N/A	3.1	5740±65
18089	Cnoc Coig	N/A	-13.6	15.2	N/A	N/A	3.1	N/A
GUsi3943	Crow Taing	N/A	-21.4	11.1	41.6	14.6	3.3	N/A
GU40816	Embo	N/A	-21.6	11.0	28.8	10.2	3.3	4403±31
GU41553	Holm of Papa Westray	BAG4 – SAMPLE 1	-20.9	9.9	42.3	15.1	3.3	4651±33
GU41554	Holm of Papa Westray	BAG4 – SAMPLE 2	-19.2	10.5	32.8	12.3	3.1	4697±33
GU41555	Holm of Papa Westray	3 E 3 Sample 1	-18.4	10.8	40.4	14.3	3.3	4754±36

Sample ID	Site name	Context	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio	^{14}C Age (^{14}C yrs BP±1σ)
GU41556	Holm of Papa Westray	3 E 3 Sample 2	-19.8	11.1	38.8	13.6	3.3	4525±36
GU36228	Loch Borralie	N/A	-20.7	9.3	41.7	14.9	3.3	4743±31
GU36229	Loch Borralie	N/A	-19.7	9.7	41.0	14.7	3.3	4875±32
GU40817	Quoyness	N/A	-20.4	10.8	39.0	13.9	3.3	4567±31
GU41549	Quoyness	N/A	-20.1	12.4	36.9	13.2	3.3	4384±36
GU40818	Raschoille cave	ORC III 13.18	-21.9	8.4	20.0	6.7	3.5	4550±29
GU40819	Raschoille cave	ORC III 15.13	-21.7	7.7	37.8	13.4	3.3	4738±31
GU40820	Raschoille cave	ORC IV 34.8	-21.6	7.7	36.3	12.9	3.3	4817±31
GU40821	Raschoille cave	ORC II 95.2	-22.1	8.8	40.5	14.4	3.3	4490±29
GU40822	Raschoille cave	ORC III 12.10	-21.5	9.2	28.5	10.1	3.3	4499±29
GU40823	Raschoille cave	ORC I 2	-21.9	9.5	37.8	13.4	3.3	4668±29
GU40824	Raschoille cave	ORC I 2	-22.3	10.2	34.6	12.4	3.2	4432±31
GU40825	Raschoille cave	ORC I 2	-22.4	10.4	41.1	14.6	3.3	4731±29
GU40826	Raschoille cave	ORC III 31.32	-22.2	9.3	39.9	14.0	3.3	4638±31
GU41551	Tulach an t'Sionnach	N/A	-21.1	10.1	37.6	13.4	3.3	4851±34
GU41552	Tulloch of Assery A	LC/TAA /25b- 10	-21.1	10.1	31.3	11.5	3.2	4796±37

Sample ID	Site name	Context	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio	^{14}C Age (^{14}C yrs BP±1σ)
GU41550	Tulloch of Assery B	LC/TAB /58	-21.6	9.8	28.1	10.6	3.1	4911±32

Table 5.25 Stable carbon and nitrogen isotope values of terrestrial herbivores from Carding Mill Bay, Oban, Scotland. Medium mammals are defined as either sheep/goats or roe deer, large mammals are defined as either cattle or red deer

Sample ID	Species	Context	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi3497	medium mammal	VI	-21.6	3.5	40.1	14.5	3.2
GUsi3498	large mammal	IV	-23.3	3.4	40.1	14.7	3.2
GUsi3500	large mammal	IX	-22.8	2.8	19.6	6.6	3.5
GUsi3501	large mammal	IX	-23.1	3.1	24.0	8.0	3.5
GUsi3502	large mammal	IX	-22.8	2.8	21.7	7.0	3.6
GUsi3503	large mammal	VII	-22.5	2.7	19.3	6.7	3.4
GUsi3504	large mammal	XIV	-22.5	3.1	40.5	14.7	3.2
GUsi3505	large mammal	XIV	-23.2	3.7	31.2	11.0	3.3
GUsi3506	large mammal	XIV	-22.5	2.4	44.7	16.2	3.2
GUsi3507	medium mammal	XIV	-22.9	3.7	42.1	15.2	3.2
GUsi3508	large mammal	XIV	-23.2	2.3	44.0	16.1	3.2
GUsi3509	red deer	XVII	-23.2	3.0	30.5	10.6	3.4
GUsi3511	large mammal	XIV	-22.8	3.9	37.4	13.5	3.2
GU39625	probable cattle	XIV	-23.3	3.5	N/A	N/A	3.3
GU39626	probable cattle	XIV	-23.2	3.3	N/A	N/A	3.3
GU39627	probable cattle	XIV	-23.3	3.5	N/A	N/A	3.3
GU39628	probable cattle	XIV	-23.4	3.4	N/A	N/A	3.3
GU39629	probable cattle	XV	-22.6	3.8	N/A	N/A	3.3
GU39630	probable cattle	XV	-23.3	4.2	N/A	N/A	3.3
GU39631	probable cattle	XV	-23.4	3.4	N/A	N/A	3.4
GU39632	probable cattle	XV	-22.0	3.0	N/A	N/A	3.3

Table 5.26 Stable carbon and nitrogen isotope of terrestrial herbivores from Links of Noltland, Westray, Scotland

Sample ID	Species	Context	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	%C	%N	C/N atomic ratio
GUsi3610	cattle	9681	-22.0	5.0	15.2	5.3	3.3
GUsi3611	cattle	9681	-21.5	5.5	24.9	9.0	3.2
GUsi3612	cattle	9690	-21.4	5.1	25.3	9.3	3.2
GUsi3613	cattle	9690	-21.8	5.2	25.6	9.3	3.2
GUsi3614	cattle	9690	-21.7	5.4	28.9	10.4	3.2
GUsi3615	cattle	9690	-21.4	5.1	23.0	8.2	3.3
GUsi3616	cattle	9690	-21.5	5.6	27.8	10.1	3.2
GUsi3617	cattle	9690	-21.6	4.7	26.4	9.6	3.2
GUsi3618	cattle	9690	-21.6	6.1	21.2	7.5	3.3
GUsi3619	cattle	9861	-21.7	5.2	19.8	7.0	3.3
GUsi3620	red deer	9861	-21.8	5.0	21.3	7.6	3.3
GUsi3621	red deer	9861	-22.3	6.3	13.8	4.8	3.4
GUsi3622	red deer	9861	-22.0	6.6	31.4	11.3	3.2
GUsi3623	red deer	9690	-22.3	6.0	24.4	8.7	3.3
GUsi3624	sheep	9681	-20.7	7.4	43.3	15.7	3.2
GUsi3625	sheep	9681	-21.5	6.8	37.7	13.9	3.2
GUsi3626	sheep	9681	-20.9	8.7	25.5	9.3	3.2
GUsi3627	sheep	9681	-20.9	6.6	33.6	12.4	3.2
GUsi3628	sheep	9681	-21.4	6.8	35.6	13.1	3.2
GUsi3629	sheep	9690	-20.7	6.3	36.8	13.4	3.2
GUsi3630	sheep	9690	-20.7	6.3	37.2	13.5	3.2
GUsi3631	sheep	9690	-21.2	6.7	33.9	12.4	3.2
GUsi3632	sheep	9690	-21.2	5.9	37.3	13.7	3.2
GUsi3633	sheep	9690	-20.1	7.9	36.9	13.4	3.2

Table 5.27 Stable carbon and nitrogen isotope values of terrestrial herbivores from Pool, Sanday, Scotland

Sample ID	Species	Context	$\delta^{13}C‰$	$\delta^{15}N‰$	%C	%N	C/N atomic ratio
GUsi3518	sheep/goat	1	-20.7	5.6	42.9	15.8	3.2
GUsi3519	sheep/goat	1	-21.1	9.5	44.4	16.2	3.2
GUsi3520	cattle	1	-22.1	5.7	43.2	15.7	3.2
GUsi3521	cattle	1	-21.6	5.2	43.6	16.0	3.2
GUsi3522	cattle	1	-22.0	5.0	33.0	11.7	3.3
GUsi3523	cattle	1	-21.8	5.1	44.4	16.3	3.2
GUsi3525	probable cattle	1	-21.5	4.9	44.9	16.4	3.2
GUsi3526	probable cattle	1	-21.7	7.6	41.2	15.1	3.2
GUsi3527	probable sheep/goat	2	-21.8	6.4	36.4	13.0	3.3
GUsi3528	probable sheep/goat	2	-21.0	7.2	42.4	15.6	3.2
GUsi3529	probable sheep/goat	2	-21.2	6.7	43.3	15.8	3.2
GUsi3530	probable cattle	2	-21.7	5.9	17.9	6.4	3.3
GUsi3531	probable cattle	2	-21.7	6.7	24.0	8.6	3.3
GUsi3532	cattle	2	-21.2	4.4	40.8	14.6	3.3

Table 5.28 Stable carbon and nitrogen isotope values of terrestrial herbivores from Risga, Loch Sunart, Scotland

Sample ID	Species	Context	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C/N atomic ratio
GUsi3485	roe deer	N/A	-21.8	2.0	30.1	10.8	3.2
GUsi3487	red deer	N/A	-21.8	2.1	33.8	11.9	3.3
GUsi3488	red deer	N/A	-22.1	2.4	40.4	14.2	3.3
GUsi3489	red deer	N/A	-22.1	2.5	36.3	12.7	3.3
GUsi3491	red deer	N/A	-21.9	1.3	20.8	7.1	3.4
GUsi3492	red deer	N/A	-22.5	2.7	30.4	10.6	3.3
GUsi3493	red deer	N/A	-22.0	2.6	22.8	7.8	3.4
GUsi3486	red deer	N/A	-29.3	8.6	1.5	0.1	15.9
GUsi3490	red deer	N/A	-31.0	3.0	1.4	0.2	9.8
GUsi3495	pig	N/A	-22.3	2.2	24.5	8.5	3.4
GUsi3496	pig	N/A	-21.2	5.0	24.8	8.6	3.4

Table 5.29 Stable carbon and nitrogen isotope values of terrestrial herbivores from Ulva Cave, Ulva

Sample ID	Species	Context	$\delta^{13}C$‰	$\delta^{15}N$‰	%C	%N	C/N atomic ratio
GUsi3748	red deer	F3	-24.5	4.9	38.5	13.8	3.3
GUsi3849	cattle	F3	-22.8	3.8	39.5	14.0	3.3
GUsi3850	cattle	F3	-21.9	1.4	38.9	13.8	3.3
GUsi3851	cattle	F3	-21.3	1.2	34.2	12.1	3.3
GUsi3852	red deer	F3	-21.8	0.8	38.4	13.5	3.3
GUsi3853	red deer	F3	-22.2	3.8	39.4	14.1	3.3
GUsi3854	sheep	F3	-22.2	5.7	35.8	12.6	3.3
GUsi3855	red deer	F3	-21.6	1.6	34.7	12.0	3.4

5.4.2 Sulfur isotope measurements of archaeological fauna

Stable sulfur isotope values from a limited number of faunal samples are arranged in Table 5.29; there are fewer sulfur isotope measurements than there are carbon and nitrogen measurements because it was clear at an early point in this research that sulfur measurements would not be suitable for use in FRUITS dietary reconstructions. While the sulfur isotope measurements passed all quality control tests (see section 5.2), the results from measurement of ancient herbivores from four sites (see Table 5.30) are indicative of a sea-spray effect, whereby marine sulfur is directly ingested by animals that graze near the sea (Wadleigh et al., 1994).

The expected range of $\delta^{34}S$ values of terrestrial samples is approximately 0 to 12‰ (Nehlich, 2015). However, the range observed in the measured samples is 17.7 to 21.0‰ and $\mu = 19.6 \pm 0.8$‰, which is expected of samples fauna influenced by marine sea spray. This sea-spray effect has also been observed in human bone collagen from individuals who lived in Scotland during the Neolithic, Bronze Age and Iron Age (Richards et al., 2001). The values of the fauna measured in this research indicate that they were likely to have been raised locally and not transported from distances inland. These results were expected of the red deer samples analysed at Carding Mill Bay, Risga and Ulva because these were wild animals that would not have been subjected to anthropogenic influences (e.g. being traded or moved from over long distances). The fact that the domestic animals also have this sea-spray effect tells us that subsistence practices during the Neolithic at Carding Mill Bay, Pool and Ulva involved raising local animals and not sourcing their livestock from inland. Because the sulfur isotope measurements were indicative of the environment the animals were raised in and not of the diet the animals consumed, they were not appropriate dietary proxies and therefore excluded from further discussion regarding human diet.

Table 5.30 Stable sulfur isotope values of terrestrial herbivores from Carding Mill Bay, Links of Noltland, Pool, Risga and Ulva, Scotland

Sample ID	Species	Site name	Context	$\delta^{34}S‰$	%S	N/S atomic ratio	C/S atomic ratio
GUsi3497	medium mammal	Carding Mill Bay	VI	18.7	0.17	192	619
GUsi3498	large mammal	Carding Mill Bay	IV	20.8	0.16	207	661
GUsi3500	large mammal	Carding Mill Bay	IX	19.6	0.12	127	441
GUsi3502	large mammal	Carding Mill Bay	IX	20.0	0.11	149	533
GUsi3503	large mammal	Carding Mill Bay	VII	19.9	0.13	121	409
GUsi3504	large mammal	Carding Mill Bay	XIV	20.3	0.19	181	580
GUsi3506	large mammal	Carding Mill Bay	XIV	21.0	0.17	218	699
GUsi3507	medium mammal	Carding Mill Bay	XIV	20.1	0.20	173	560
GUsi3508	large mammal	Carding Mill Bay	XIV	20.9	0.17	223	712
GUsi3509	red deer	Carding Mill Bay	XVII	20.3	0.15	167	561
GUsi3624	sheep	Links of Noltland	9681	18.0	0.27	135	434
GUsi3518	sheep/goat	Pool	1	18.7	0.26	140	444
GUsi3519	sheep/goat	Pool	1	17.7	0.27	140	446
GUsi3520	cattle	Pool	1	19.0	0.27	133	425
GUsi3521	cattle	Pool	1	19.4	0.26	141	449
GUsi3523	cattle	Pool	1	19.5	0.26	145	461

Sample ID	Species	Site name	Context	$\delta^{34}S‰$	%S	N/S atomic ratio	C/S atomic ratio
GUsi3525	probable cattle	Pool	1	19.2	0.27	139	443
GUsi3528	probable sheep/goat	Pool	2	18.9	0.25	143	453
GUsi3529	probable sheep/goat	Pool	2	20.4	0.26	137	440
GUsi3487	red deer	Risga	N/A	18.9	0.20	139	462
GUsi3488	red deer	Risga	N/A	19.2	0.20	162	536
GUsi3489	red deer	Risga	N/A	19.5	0.20	142	475
GUsi3491	red deer	Risga	N/A	19.6	0.15	106	364
GUsi3492	red deer	Risga	N/A	19.1	0.20	121	404
GUsi3493	red deer	Risga	N/A	19.8	0.17	106	360
GUsi3850	cattle	Ulva	F3	19.6	0.19	163	534
GUsi3853	red deer	Ulva	F3	20.6	0.21	150	489

5.4.3 Stable carbon isotope and radiocarbon measurements of marine and terrestrial fauna

Eight limpet shells and eight fragments of cattle bone were sampled from Carding Mill Bay in order to produce a new ΔR value for the site. Samples were taken from two contexts at the midden (XIV and XV) which both had human remains present within. The results of $\delta^{13}C$ analysis and radiocarbon dating of these samples are presented in Table 5.31. This data was then used to calculate the ΔR value as follows: outliers in the radiocarbon data were initially excluded using a χ^2 test; the ΔR value was then determined using the multiple paired marine/terrestrial sample approach, whereby a ΔR value was calculated for all possible pairs and then a weighted mean paired offset was calculated for the context, with the variability expressed as the standard error for predicted values (Cook et al., 2015).

Table 5.31 ^{14}C and $\delta^{13}C$ measurements of marine shell and terrestrial herbivore bone collagen from Carding Mill Bay for ΔR determination

Context number	Sample ID	Sample type	^{14}C age (yr BP ± 1σ)	$\delta^{13}C$ (‰ VPDB)
XIV	GU39625	Terrestrial	5273±39	-23.3
XIV	GU39626	Terrestrial	5190±36	-23.2
XIV	GU39627	Terrestrial	5040±37	-23.3
XIV	GU39628	Terrestrial	4848±38	-23.4
XIV	GU39633	Marine	5413±28	0.6
XIV	GU39634	Marine	5522±28	-0.2
XIV	GU39635	Marine	5424±29	0.2
XIV	GU39636	Marine	5395±28	0.8
XV	GU39629	Terrestrial	5334±39	-22.6
XV	GU39630	Terrestrial	5320±39	-23.3
XV	GU39631	Terrestrial	5155±39	-23.4
XV	GU39632	Terrestrial	5278±36	-22.2
XV	GU39637	Marine	5519±28	0.6
XV	GU39638	Marine	5467±29	0.4
XV	GU39639	Marine	5575±29	0.9
XV	GU39640	Marine	5573±28	0.1

Table 5.32 Results of χ^2 tests on all ^{14}C ages for terrestrial and marine samples from contexts XIV and XV at Carding Mill Bay

Context number	**Terrestrial χ^2 T value**	**Marine χ^2 T value**
XIV	72.10 ($\chi^2_{:0.05}$ = 7.81)	12.39 ($\chi^2_{:0.05}$ = 7.81)
XV	13.07 ($\chi^2_{:0.05}$ = 7.81)	9.56 ($\chi^2_{:0.05}$ = 7.81)

Table 5.33 Data for contexts XIV and XV at Carding Mill Bay that contained inconsistent measurements on the basis of χ^2 tests

Context	**Consistent measurements**	**Age BP±1σ**	**Inconsistent measurements**	**Age BP±1σ**	**T value**
XIV (terrestrial)	No consistent terrestrial measurements were identified, therefore a judgement call was made to include all measurements when calculating the ΔR value.		GU39625 GU39626 GU39627 GU39628	5273±39 5190±36 5040±37 4848±38	72.10
XIV (marine)	GU39633 GU39635 GU39636	5413±28 5424±29 5935±28	GU39634	5522±28	3.55
XV (terrestrial)	GU39629 GU39630 GU39632	5334±39 5320±39 5278±36	GU39631	5155±39	1.23
XV (marine)	GU39637 GU39639 GU39640	5519±28 5575±29 5573±28	GU39638	5467±29	2.54

Consistent measurements were used to calculate values of ΔR. T-statistics shown are for consistent groups.

Tables 5.32 and 5.33 show the statistical treatment of the data used to calculate ΔR values for contexts XIV and XV at Carding Mill Bay. For context XIV marine samples, one sample (GU39634) was excluded as an outlier and the remaining three samples passed the χ^2 test. However, the terrestrial samples failed the χ^2 test completely, with no two samples passing.

On that basis, it was determined that context XIV is mixed and unsuitable for deriving a ΔR value. For context XV, one marine and one terrestrial sample (GU39638 and GU39631, respectively) were removed and the remaining three samples in both groups passed the χ^2 test. In this case, context XV was deemed suitable for ΔR calculation, and the calculated value was -130 ± 34 ^{14}C yrs.

Chapter 6: Discussion

6.1 Introduction

There are three topics of discussion that are addressed in this chapter: 1) the suitability of including modern analogue samples in archaeological stable isotope dietary studies will be evaluated, 2) the faunal baselines from each archaeological site will be scrutinised to investigate whether there are any geographical differences between the isotope values of the populations and 3) the dietary estimates and radiocarbon dates from human remains will be discussed in the context of dietary change in the Mesolithic-Neolithic transition.

There are several reasons for approaching the discussion of the data in this way. Considering the issues surrounding modern analogue samples first will allow the definition of some of the important data required for dietary interpretation of the human samples using FRUITS. By performing statistical testing and discussing the implications of the archaeological faunal isotope measurements in the second section of this chapter, we can add to the dataset required for the FRUITS models. The findings from this discussion of faunal data will be used to address the third and possibly most crucial aspect of this thesis: what the radiocarbon and stable isotope measurements can tell us about how human diet changed over the Mesolithic-Neolithic transition in Scotland. The stringent consideration of samples and offsets included in the FRUITS models means that the resulting dietary reconstructions and the radiocarbon calibrations that use them are as reliable and accurate as possible; this will result in an in-depth view of patterns in marine consumption during the Mesolithic-Neolithic transition.

6.2 Modern Faunal Samples

Questions addressed here about modern faunal samples used in this project are:

1. What are the appropriate stable isotope tissue offset values of different terrestrial and marine species in order to build an accurate reconstruction of palaeodiet?
2. Do these isotope offsets show any distinction according to species?
3. Are modern marine and terrestrial fauna suitable analogues for inclusion in archaeological faunal stable isotope baselines?

6.2.1 Stable isotope tissue offsets for FRUITS dietary models

It is essential to know the difference in isotope values between the measured sample (fish and mammal bone collagen) and the meat of the fish/mammal consumed by human populations (muscle) as the latter are the data required by FRUITS in order to recreate human diet. Stable isotope tissue offsets were calculated for sites in Scotland to ensure that the most accurate dietary data are used in FRUITS when modelling past diet. The food values used in FRUITS were derived from stable isotope values of faunal remains that were found in an isotopically comparable environment to archaeological human individuals whose diet is being investigated. Strict sample selection criteria were applied to the faunal remains to ensure that an appropriate isotopic baseline was utilised: where possible, samples were taken from the same location and time period as the human samples, where this was not possible, the isotope values of species-matched analogues were scrutinised and compared against the rest of the faunal data set to ensure that the baseline reflected the best approximation of the past isotope environment. These values were converted from the bone collagen measurements to the isotopic values of the food consumed by human individuals to provide the 'food values' data required for each FRUITS model.

Tissue offset values used to convert the faunal bone collagen isotope data to food values to use in FRUITS usually follow those utilised by Fernandes et al. (2015) which are average values with associated errors from several published papers; see Table 6.1 and 6.2 for a comparison between Fernandes' offset values and the values produced for this research (Vogel, 1978, Tieszen and Fagre, 1993, Sholto-Douglas et al., 1991, Pinnegar and Polunin, 1999, Fischer et al., 2007, Warinner and Tuross, 2009, Warinner and Tuross, 2010). While Fernandes' approach of producing an average value from several studies is the best method of deriving tissue offsets without producing values specifically for each country, region or site, these values are not necessarily representative of those for sites in Scotland. Tissue offset values may vary according to species and potentially according to global location (Caut et al., 2009, Froehle et al., 2010), therefore $\Delta^{13}C_{protein\text{-}collagen}$ and $\Delta^{15}N_{protein\text{-}collagen}$ values, which are the differences between the $\delta^{13}C$ and $\delta^{15}N$ measurements of bone collagen and flesh, for Scottish species were produced for terrestrial herbivores, marine shellfish and marine fish (Tables 6.1 and 6.2). These were used in each FRUITS model to convert the faunal baseline bone collagen measurement to a food value.

Examining the $\Delta^{13}C_{protein\text{-}collagen}$ offset values for terrestrial fauna in this study, the values range from -1.6 to -2.3‰, all with relatively small ranges (see Table 6.1). These data show that, in general, terrestrial mammal bone collagen is enriched in ^{13}C in comparison to flesh. The differences in $\delta^{13}C$ values of different body tissues is well documented and is a result of isotopic fractionation when carbon is incorporated into different body tissues (DeNiro and Epstein, 1978, Tieszen et al, 1983, Tieszen and Fagre 1993). There appears to be two groups within the terrestrial offsets: large mammals (cattle and red deer) with offset values of -1.7‰ and -1.6‰, respectively, and medium mammals (sheep and roe deer) with values of -2.2‰ and -2.3‰, respectively. The number of sample groups and the number of individuals analysed is not sufficient to make any conclusive assertions about these two groups, however the data presented in Table 6.1 suggest that dietary differences due to body size may be a factor influencing isotopic offset between bone collagen and muscle. However, when considering the errors associated with these values (Table 6.1), the difference between the two groups is slight. The relationship between body size and tissue stable isotope values has been investigated in marine species, but not terrestrial examples (Sholto-Douglas et al., 1991, Jennings et al., 2001). Further research with larger sample populations, and a larger range of small, medium and large species would be required to test this hypothesis.

The same pattern in tissue offsets is not observed in terrestrial $\Delta^{15}N_{protein\text{-}collagen.}$ Sheep, red deer and roe deer have very similar values (+0.4‰, +0.3‰ and +0.5‰ respectively), while cattle have a tissue offset value of -0.9‰. The best explanation for the larger $\Delta^{15}N_{protein\text{-}collagen}$ in cattle is that the value does not reflect a true species related difference in offsets because the small sample size of three individuals is not adequately representative of the population. Ultimately, the $\Delta^{15}N_{protein\text{-}collagen}$ offset values show there is very little difference between nitrogen isotope ratios in the different tissues measured. This suggests that nitrogen is incorporated into bone and flesh with similar kinetic isotope fractionation effect and with little difference observed between different species or between animals of different sizes.

Table 6.1 New $\Delta^{13}C_{protein\text{-}collagen}$ and $\Delta^{15}N_{protein\text{-}collagen}$ tissue offset values for terrestrial herbivores compared to the same values calculated by Fernandes, et al. (2015). N/A= no value was calculated.

	Values produced in this research (‰)		**Values produced by Fernandes, et al. (2015) (‰)**	
Species	**$\Delta^{13}C$ protein-collagen**	**$\Delta^{15}N$ protein-collagen**	**$\Delta^{13}C$ protein-collagen**	**$\Delta^{15}N$ protein-collagen**
Cattle	-1.7±0.1	-0.9±0.2	N/A	N/A
Sheep	-2.2±0.6	+0.4±1.0	N/A	N/A
Red deer	-1.6±0.4	+0.3±0.7	N/A	N/A
Roe deer	-2.3±0.2	+0.5±0.5	N/A	N/A
TERRESTRIAL AVERAGE	-1.9±0.5	+0.3±0.8	-2	+2

There are similar trends in the marine tissue offset compared to the terrestrial values (Table 6.2). All three species of fish bone collagen to muscle tissue offsets showed relatively uniform $\Delta^{13}C_{protein\text{-}collagen}$ offset values, with a range of -2.6 to -2.7‰ for carbon offsets and -0.2 to -0.5‰ for $\Delta^{15}N_{protein\text{-}collagen}$ offsets. This suggests that the marine species analysed share more physiological similarities with each other in comparison to the similarities between the terrestrial species. This hypothesis is backed up by the fact that all the fish sampled were closely related omnivorous pelagic species; however, as with the terrestrial fauna, further investigation of a larger number of individuals would be necessary to reliably test this hypothesis.

Table 6.2 New $\Delta^{13}C_{protein\text{-}collagen}$ and $\Delta^{15}N_{protein\text{-}collagen}$ tissue offset values for marine fish compared to the same values calculated by Fernandes, et al. (2015). N/A= no value was calculated.

	Values produced in this research		**Values estimated by Fernandes, et al. (2015)**	
Species	**$\Delta^{13}C$ protein-collagen**	**$\Delta^{15}N$ protein-collagen**	**$\Delta^{13}C$ protein-collagen**	**$\Delta^{15}N$ protein-collagen**
Cod	-2.6±0.5	+0.5±0.2	N/A	N/A
Pollock	-2.7±0.4	+0.2±0.5	N/A	N/A
Haddock	-2.7±0.3	+0.3±0.5	N/A	N/A
MARINE AVERAGE	-2.7±0.4	+0.4±0.4	-1	+2

In both marine and terrestrial sample populations, the tissue isotope offset values calculated in this thesis do not show significant variation according to species. In comparison to tissue offset values calculated by Fernandes et al. (2015), there is good agreement between values for $\Delta^{13}C_{protein\text{-}collagen}$ in terrestrial fauna. In all other calculations; however, there are differences between the known species offset and the values estimated by Fernandes et al. (2015); see Tables 6.1 and 6.2. The calculated tissue offset values produced during this research were considered to be optimum when modelling the diet of Scottish Mesolithic and Neolithic humans since they were known values and not estimated consensus values, and the data are produced from representative species in each dietary baseline, as opposed to a range of species from the literature. The data produced in this research also have the advantage of individually calculated error values associated with each offset value, as opposed to the figures used by Fernandes et al. (2015) which do not have associated errors. For this reason, the values that were applied to bone collagen isotope baseline measurements when producing 'food group' values in FRUITS were an average terrestrial offset value with the error expressed as the standard error of the mean and a marine average offset value with the same error calculation.

6.2.2 Modern samples as analogues for ancient fauna

A substantial branch of this research aimed to find out whether modern faunal samples can be used to supplement ancient samples in a stable isotope dietary baseline. The reason for this investigation are that many stable isotope dietary studies contain insufficient, or are devoid of, stable isotope measurements of faunal remains that are spatially and chronologically comparable to the humans under investigation. This is either because samples are not available for measurement, or no faunal remains survive to be measured – the latter is particularly true for the Scottish Mesolithic and Neolithic (see Chapter 2 for a review of the relevant literature). A faunal baseline is essential for accurate interpretation of human diet using stable isotopes to correct the human data for natural geological and human induced variation in isotope values that are reflected in every stage of the food-chain (Peterson and Fry, 1987). The ability to use modern samples in place of ancient fauna would allow stable isotope researchers to consistently produce reliable dietary reconstructions, even when faunal remains are not present on a site.

Two types of modern marine samples were analysed to aid in the investigation of ancient diet: fish and shellfish. All of the modern marine samples were sourced from the same geographic locations as the ancient fish, i.e. just off the coast of Scotland. Considering the marine fish first, lipid free bone collagen values were used when comparing against ancient samples and a known offset was applied to take into account the Suess Effect, which is the alteration of stable carbon isotope values in modern samples as a result of the release of fossil fuel CO_2 into the atmosphere (Suess, 1958). Once the modern values were adjusted for the Suess Effect (0.86‰ for modern marine samples (Beavan Athfield et al., 2008)) it can be seen in Figure 6.1 that there was significant overlap between modern and archaeological cod bone collagen isotope measurements, indicating that these chronologically distinct samples are isotopically comparable. Also, haddock bone collagen values were comparable to ancient and modern cod values in terms of carbon isotope measurements. The $\delta^{15}N$ measurements of haddock were slightly depleted in comparison to cod; this was an expected difference since cod are known to feed differently to haddock and are at a higher trophic level in the marine food web (Kohler and Fitzgerald, 1969).

Modern pollock bone collagen stable carbon isotope values are comparable to other modern and ancient marine fish values, with the exception of two outliers (GUsi4410 and GUsi4418. See table 5.5). A potential cause of the outlying measurements could be that lipids were not

fully extracted from the bone since the $\delta^{13}C$ values of the two individuals were more negative than the rest of the population. The average $\Delta^{13}C_{\text{lipid free bone collagen-bone collagen}}$ value for pollock is -0.7 ± 0.3‰ and the offsets between the two outliers are 0.5‰ and 0.7‰ (see Table 6.2). Pollock bone collagen $\delta^{15}N$ values were less enriched compared to modern and ancient cod and modern haddock. The sampled pollock in this research were considerably smaller (approximately 50% smaller) than both the cod and the haddock. While body size is not a physiological factor that determines nitrogen isotope values in fish muscle when the diet is unvarying (Sweeting et al., 2007), differences in $\delta^{15}N$ isotope values could be as a result of feeding differences that result from these animals having different body sizes (Sholto-Douglas et al., 1991, Jennings et al., 2001). The fact that all modern and ancient stable carbon isotope values of marine fish were comparable suggests that modern baseline stable carbon values for the North Sea are analogous to ancient baseline measurements, and it follows that other marine samples are likely to be analogous.

Figure 6.1 Stable carbon and nitrogen isotope measurements of archaeological and modern marine fish bone collagen from the North Sea. Modern samples have been corrected for the Suess Effect (Beavan Athfield et al., 2008).

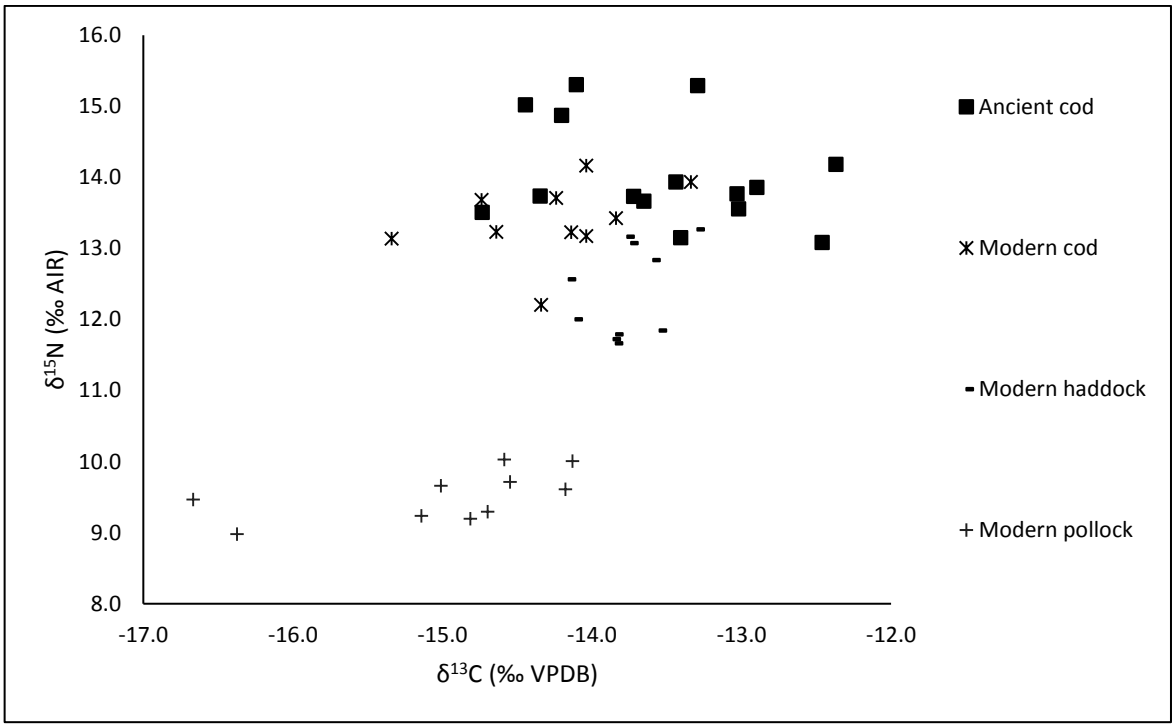


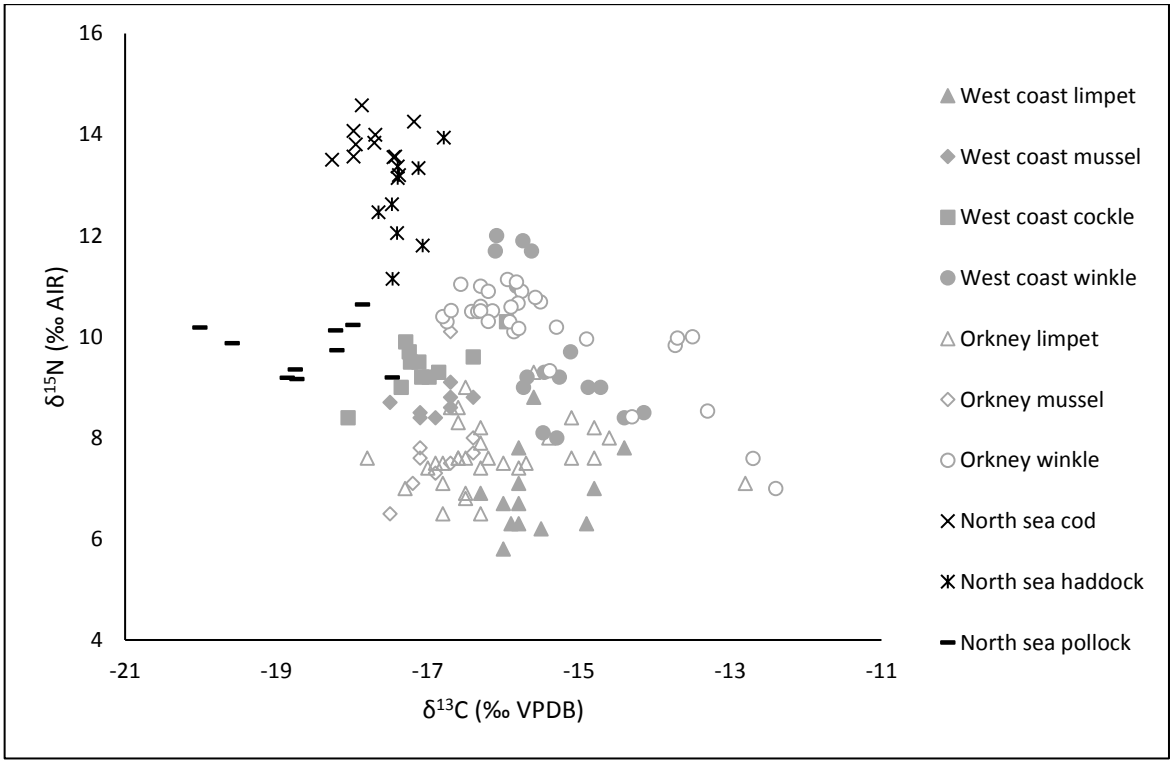
Figure 6.2 shows the stable isotope measurement of modern shellfish in comparison to modern fish; these data were used to determine whether the shellfish samples were suitable for inclusion in the ancient dietary baselines. Average $\delta^{13}C$ values ranged from -17.1‰ to -15.4‰ between all species of shellfish while $\delta^{15}N$ ranged from 8.1‰ to 10.3‰ (see tables 5.19 and 5.20). The ranges in isotope values for shellfish can be attributed to differing dietary habits of each species: filter feeders, such as mussels, consume phytoplankton while shoreline grazers, such as limpets, consume algae, and winkles are omnivorous, eating both algae and other shellfish. A direct comparison between modern and ancient marine shellfish flesh is impossible since flesh from Mesolithic and Neolithic shellfish is not preserved. A comparison was therefore made between modern fish muscle and modern shellfish muscle.

To confirm whether shellfish were appropriate analogues for ancient samples, the known isotopic differences between fish and shellfish from the same locality were considered before a comparison between the measured samples was made. It has been shown that muscle $\delta^{13}C$ isotope values from oceanic invertebrates are on average 2.4‰ higher than pelagic fish muscle (Sherwood and Rose, 2005), and that these differences may be due to dietary source differences (shallow water vs. deeper ocean food sources) and variation in lipid content in different oceanic species (France, 1995, Kaehler et al., 2000). The average carbon isotope difference between fish and shellfish muscle in this research was 2.3‰, which reflects this predicted difference between benthic shellfish and pelagic fish (See Table 5.19).

It was also observed that shellfish muscle was depleted in ^{15}N compared to fish by 3.4‰. This isotopic difference was predicted as it reflects the differences in fauna that are on different trophic levels in a food chain (see Chapter 3.2.2). Shellfish measurements in this research were one trophic level below the fish. We can attribute these isotopic differences observed between fish and shellfish tissue to known and quantifiable dietary factors. Shellfish feed by grazing on algae growing on rocks or by filtering algae from the ocean water. The food chain involved here is very short, since algae fix carbon directly from the bicarbonate within the ocean water. On the other hand, there are many more steps in the food chain between the bottom of the food chain (algae) and the fish species considered in this research (cod, haddock and pollock). The much longer food chain results in fish and shellfish occupying different nitrogen trophic levels. Therefore, it can be argued that these differences do not result from natural geographical isotope variation or environmental contamination. Therefore, it is reasonable to assert that the measured shellfish samples were isotopically

comparable to ancient shellfish values and that the modern shellfish were suitable for inclusion in the ancient dietary baselines.

Figure 6.2 Stable carbon and nitrogen isotope values of modern fish and shellfish muscle protein from Orkney and the west coast of Scotland. Modern samples have been corrected for the Suess Effect (Beavan Athfield et al., 2008).



Considering the results obtained on shellfish from different geographic regions, a comparison between the isotope values of shellfish from Orkney and shellfish from the west coast of Scotland shows substantial overlap (Figure 6.2). This shows there are no major differences between the isotope values of shellfish muscle that come from different locations, and therefore shellfish from the two areas are largely isotopically comparable. The hypothesis was tested using independent sample t-tests: no significant difference was found between the carbon isotope values of shellfish from the west coast (μ = -16.1, σ = 0.9) and shellfish from Orkney (μ = -15.9, σ = 1.1). Equal variances were assumed, t (119) = 0.753 and P = 0.453. The same test found no significant difference between nitrogen isotope values of shellfish from the west coast (μ = 8.7, S = 1.5) and shellfish from Orkney (μ = 8.8, S = 1.5). Equal variances were assumed, t (119) = 0.175 and P = 0.862. The homogeneity of the

isotope values of the shellfish sample population means that these samples are interchangeable in a dietary baseline over the full study area.

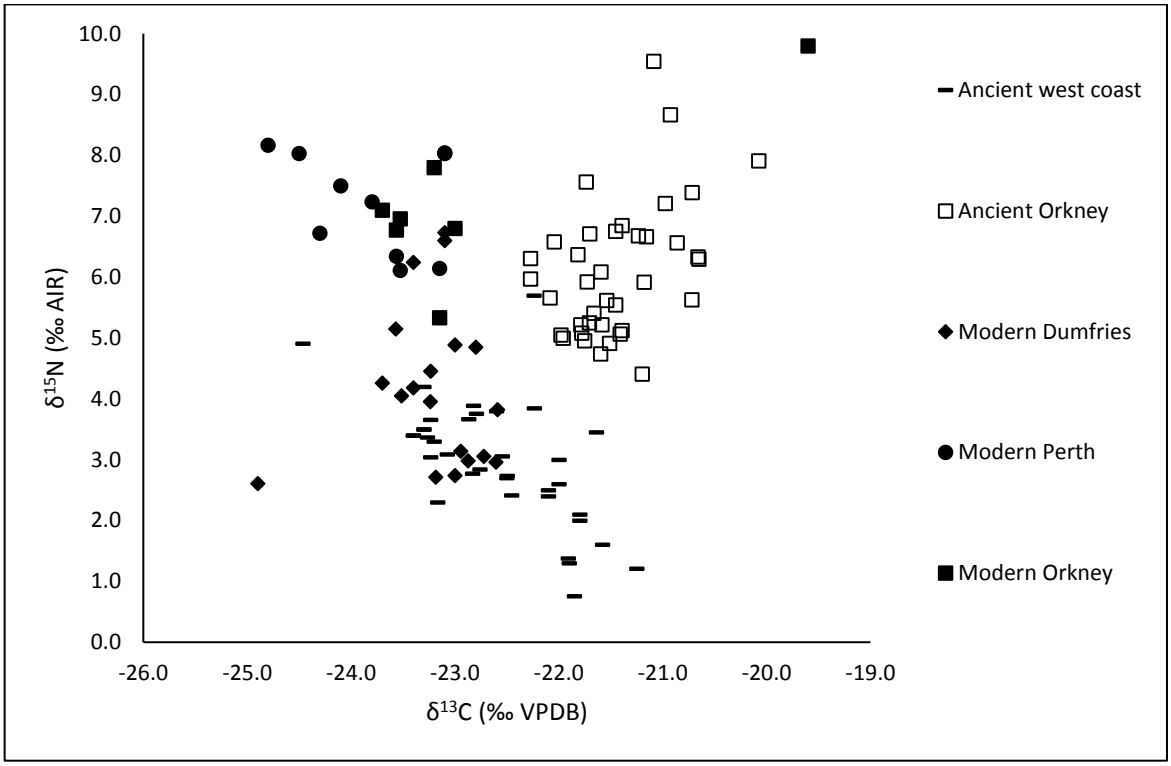
Being able to use modern fish and shellfish in an ancient isotope faunal baseline is of great value to dietary studies using stable isotope analysis. Fish remains are often found on archaeological sites; however, because of sampling biases, bones are unrepresentatively recovered unless fine sieving is carried out during excavation. There are occasions where we can be sure that fish are present on site, but insufficient bones survive to produce multiple isotope measurements for a representative faunal baseline: this is the case at all sites considered in this study. Having the option to build a baseline using modern fish allows researchers to fill the gaps that this situation causes. It is also very helpful to dietary reconstruction of humans in this research that we can include shellfish as a food group in isotope faunal baselines. The edible organic portion of shellfish does not survive in the archaeological record, but as demonstrated here, this food source is isotopically distinct from marine fish. When recreating the diet of people who may have consumed shellfish, and especially when using Bayesian modelling such as FRUITS, it is essential to include this source in the isotope baseline to produce accurate estimations of relative food group contributions to the diet.

There were no differences between modern and ancient fish isotope values of geographically distinct samples. This similarity in isotope values suggests that the marine environment, for this range of species, was spatially homogenous with respect to the isotope values from study area and these had not been significantly altered with the respect to the timeframe covered in this project (Barrett et al., 2008). With this in mind, the results of shellfish isotope measurements from this research were compared to those of oysters and mussels in the literature. Bonsall et al. (2009) used their measured values of oyster/mussel protein (-20‰) to argue that shellfish may be isotopically undetectable in the Neolithic diet because their values are so close to terrestrial fauna. While the present study did not consider oysters, and therefore cannot comment on the validity of the conclusions regarding oysters, measurements on four different species (including mussels) suggests that the isotopic difference between fish and shellfish is not as large as previously suggested. Consequently, shellfish consumption in the Mesolithic and Neolithic may be underestimated, but it is unlikely to be masked altogether.

When searching for suitable modern terrestrial analogues for this research, there was a shortage of organic farms that were located near to the archaeological sites investigated in this thesis. In fact, only three suppliers of truly organic animal meat and bones were identified, and only one of these (G & C Parker, Sanday) was in a location which is geographically comparable with archaeological samples included in the project (Quoyness) (see Figure 4.4). When building a faunal baseline for a stable isotope dietary study, efforts must be made to ensure that faunal samples reflect the appropriate isotope baseline values for the human subjects in the study: this usually means they must be chronologically and geographically comparable, since isotope values of organisms can vary over time and space. Terrestrial samples from Perth and Dumfries were used despite them being geographically incomparable to the ancient samples because no previous study has compared modern to ancient Scottish faunal isotope values.

Considering the results of modern lipid free bone collagen from terrestrial animals, a similar procedure to the modern marine samples was followed to convert the values to ancient faunal equivalents by applying a known offset to the isotope values to account for the Suess Effect (Suess, 1958). Once the modern values are adjusted (1.5‰ for modern terrestrial samples per Beavan Athfield et al. (2008)) and compared with the ancient samples, it is apparent that the bone collagen from modern terrestrial mammals is not a suitable analogue for ancient faunal bone collagen isotope measurements (Figure 6.3). The modern and ancient herbivores from Orkney, while comparable in nitrogen isotope values, are distinct in their carbon values. This points towards continuity between nitrogen isotope values of the soil and plants over a very long time period and may even suggest that the effects of land management and climate from the Neolithic period have persisted over millennia. The fact that these two geographically equivalent populations from different time periods are distinct in their stable carbon isotope values may demonstrate that a different variety of plant matter grew in the locale in the Neolithic, compared to what is available for consumption by modern animals. This shows that modern Scottish terrestrial herbivores are not appropriate for inclusion in ancient dietary reconstructions.

Figure 6.3 Stable carbon and nitrogen isotope measurements of archaeological and modern terrestrial herbivore bone collagen from Scotland. Modern samples have been corrected for the Suess Effect (Beavan Athfield et al, 2008).



With regards to the Scottish archaeological sites, the findings of this research show that it is important that chronologically contemporaneous terrestrial faunal samples make up the isotope baseline in dietary studies. It is interesting that this is the case for terrestrial samples, but not for marine samples. The most likely reason that only fauna from the marine environment are isotopically comparable to ancient fish and shellfish is that the ocean is a far bigger, more mixed environment than the terrestrial ecosystem. Additionally, humans have had a far more profound effect on the terrestrial environment than on the oceans through intensive farming and the introduction of industrial pollutants to the ecosystem. This is inferred because the isotopic make-up of the land has altered so much since prehistory while the ocean has remained relatively close to ancient values.

6.2.3 Summary of modern faunal samples

Modern marine fish and shellfish were suitable for inclusion in ancient faunal isotope baselines and will be included in the baselines to determine values for the FRUITS models when recreating human diet in this research. However, the modern terrestrial animals measured in this project were not suitable for inclusion in the FRUITS models. Where possible, the terrestrial food group values were therefore derived from contemporary terrestrial animals that are geographically and chronologically associated with the humans in each model. Tissue offset values (derived from modern mammals and fish) were defined for both marine and terrestrial carbon and nitrogen samples to accurately convert faunal bone collagen isotope measurements to food group values for the FRUITS models. The isotopic offsets between protein and collagen were found not to vary significantly between species; therefore, average values for all marine and all terrestrial samples were used to calculate offset values.

6.3 Mesolithic and Neolithic Faunal Samples

Questions addressed here about Mesolithic and Neolithic faunal samples are:

1. Are there differences in faunal bone collagen isotope measurements between sites at the west coast of Scotland and sites on Orkney?
2. Do faunal isotope values vary between sites in the same area?

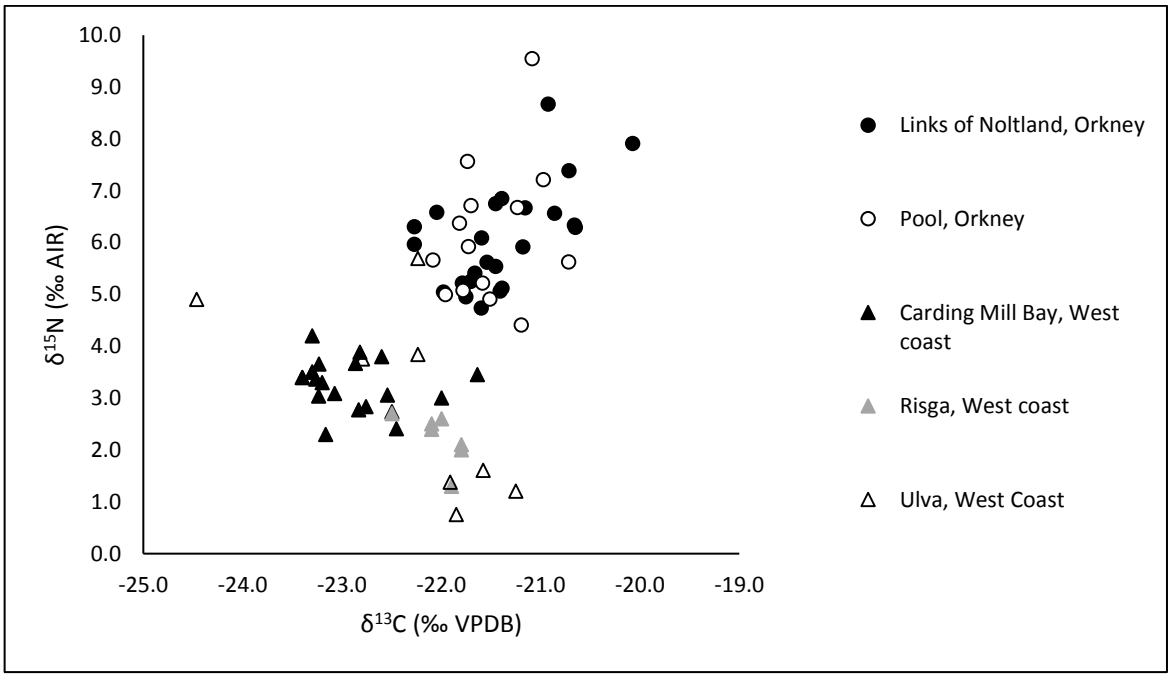
6.3.1 Comparing fauna from Orkney with those on the west coast of Scotland

The archaeological terrestrial fauna included in this research are typical of the samples that are normally included in a dietary baseline: most dietary baselines for human dietary reconstruction using isotopes are made up of terrestrial mammal species that are geographically and chronologically comparable. To determine whether it was possible to include ancient terrestrial fauna from different sites or different parts of the country in dietary baselines in Scotland, the values were tested for potential statistical differences between populations in Orkney and those on the west coast of Scotland. The rationale behind this analysis was that if ancient faunal isotope values were not site specific, then they could be

used as one large and much more isotopically representative dietary baseline for the FRUITS models. However, if they proved to be distinct, we can be sure that the most appropriate samples are utilised in each dietary reconstruction by using geographically appropriate values, (see 6.4.2 for details on how each dietary reconstruction model was calculated).

Figure 6.4 shows the isotope values of all terrestrial mammals at each archaeological site. The plot shows two distinct groups of samples: those from sites on the west coast of Scotland and those from Orkney. Statistical tests, described below, were applied to investigate whether there was any significant difference between the two groups, and between the sites within the groups. If faunal bone collagen isotope values proved to be indistinct between sites or regions, it would suggest that, for human dietary studies, it is not necessary to source an isotope baseline from the same site as the human remains within Scottish coastal regions. This would offer the opportunity to expand baseline sample sizes to make isotope values more representative of material that was consumed by humans under investigation.

Figure 6.4 Stable carbon and nitrogen isotope values of all archaeological terrestrial faunal bone collagen samples from five different sites across the West Coast of Scotland and Orkney, Scotland.



To test the hypothesis that the data from the west coast and Orkney are significantly different, an independent samples t-test was carried out. Equal variances were not assumed and there was a significant difference in the carbon isotope values of animals from the west coast (μ = -22.6, 1σ = 0.7) and those from Orkney (μ = -21.4, 1σ = 0.5); t (62.601) = 8.152, P = 0.000. There was also a significant difference in the nitrogen isotope values between the west coast (μ = 3.0, 1σ = 1.0) and Orkney (μ = 6.1, 1σ = 1.1). Equal variances were assumed; t (72) = 12.525; P = 0.000. The t-tests show that faunal samples from the west coast are isotopically distinct from the Orkney samples and therefore samples from these two areas are not interchangeable in dietary baselines.

There are a variety of plausible explanations as to why terrestrial fauna from the west coast have significantly different isotope values than equivalent species from Orkney. There is no way of verifying the most likely of the following explanations, so these must be interpreted as speculative reasons. In the case of $\delta^{13}C$ measurements, isotopic differences attributed to geographical variation have also been observed between Neolithic Orkney and the Outer Hebrides. Statistically significant differences were reported in the $\delta^{13}C$ values of sheep (0.2‰) and red deer (0.8‰) from the two areas by Jones et al. (2012). Reasons suggested for these localised isotopic differences were natural variation in the landscapes in which the two red deer populations subsisted and different farming strategies that influenced the diet of the two sheep populations (Jones et al., 2012).

In the same 2012 study, geographical variation was also observed in $\delta^{15}N$ values of fauna from Orkney and the Outer Hebrides. Differences that, again, were statistically significant were reported between samples of cattle (0.6‰) and sheep (1.0‰) from the two island groups and were attributed to different processes of nitrogen cycling in the soil (Jones et al., 2012). Jones et al argued that the most likely reason for these differences was variations of soil quality between the two areas. This may also explain the differences observed in $\delta^{15}N$ values in archaeological terrestrial fauna in this thesis; however, it must also be considered that different degrees of deliberate of natural manuring at each site could also be a contributing factor. The use of manure as a fertilizer or the addition of guano to the soil from seabird colonies has been shown to increase the $\delta^{15}N$ values of human bone collagen as animal waste is relatively enriched in ^{15}N (Bogaard et al., 2007).

6.3.2 Considering inter-site variation

Figure 6.4, showing all $\delta^{13}C$ and $\delta^{15}N$ data for archaeological fauna, was used to investigate inter-site variability of isotope measurements within the two distinct areas of Orkney and the West coast. Although it was not possible to use fauna from Orkney to supplement baselines at the west coast (and vice versa), it was important to examine whether baselines within these two areas are comparable or distinct. Where they were comparable, these samples could be used to build a more representative baseline; where they were not, a reason for this difference was sought.

It is apparent from Figure 6.4 that faunal isotope values from different sites on Orkney overlap considerably. To statistically test this, independent sample t-tests were carried out. For $\delta^{13}C$, equal variances were assumed and no significant difference was found between values from Pool ($\mu = -21.5$, $1\sigma = 0.4$) and Links of Noltland ($\mu = -21.4$, $1\sigma = 0.5$): $t(36) = 0.568$, $P = 0.574$. For $\delta^{15}N$ values, similar findings were observed; equal variances were assumed and, again, no significant difference was found between values from Pool ($\mu = 6.1$, $1\sigma = 1.3$) and Links of Noltland ($\mu = 6.1$, $1\sigma = 1.0$): $t(36) = 0.115$, $P = 0.909$. These observations demonstrate that faunal remains from the two Orkney sites were comparable and could, therefore, be used to build representative baselines for these sites and potentially for other Neolithic sites on Orkney.

Examining the faunal isotope values from different sites at the west coast of Scotland (Figure 6.4), it is less apparent through observation of the plotted isotope data whether these values are comparable. Statistical testing, described below, was carried out on the three sites of Ulva, Risga and Carding Mill Bay to investigate whether there was a significant difference between the isotope values from these sites. For $\delta^{13}C$ values, Levene's test showed a significant difference between the variances of each test group ($P = 0.033$), therefore ANOVA was not an appropriate test to apply to these values and non-parametric testing was applied instead. A Games-Howell test was applied, since this method does not assume equal variances, and a significant difference was found between the mean isotope values of Carding Mill Bay ($\mu = -22.9‰$, $1\sigma = 0.5$) and Risga ($\mu = -22.0‰$ $1\sigma = 0.2$) ($P = 0.000$). All other statistical comparisons in the Games-Howell test were found to be not significant ($P = 0.591$ for comparisons between Ulva ($\mu = -22.3‰$, $1\sigma = 1.0$) and Risga), ($P = 0.457$ for comparisons between Ulva and Carding Mill Bay).

The trends in the $\delta^{15}N$ values are very similar to those for the $\delta^{13}C$ values of Ulva, Risga and Carding Mill Bay. A Levene's test again showed that non-parametric testing was appropriate for the dataset (P = 0.000). A Games-Howell test comparing each site showed a significant difference between the $\delta^{15}N$ of fauna from Carding Mill Bay ($\mu = 3.3‰$ $1\sigma = 0.5$) and Risga ($\mu = 2.2‰$ $1\sigma = 0.5$) (P = 0.000). The same test found no significant difference between Ulva ($\mu = 2.9‰$ $1\sigma = 1.9$) and Risga (P = 0.473) and between Ulva and Carding Mill Bay (P = 0.970).

The differences observed above in both the $\delta^{13}C$ and the $\delta^{15}N$ isotope values for sites on the west coast are unlikely to be a result of natural variation over time. The differences between Carding Mill Bay and Risga could be explained because the samples measured are from different time periods (Carding Mill Bay is much a later site than Risga); however, this argument does not hold up for comparisons between Carding Mill Bay and Ulva, which are also non-contemporaneous but where the samples show no significant difference in isotope values. We must therefore conclude that sites on the west coast are not isotopically homogenous. Since the isotopic differences between these sites could not be reasonably explained, faunal baselines in the west coast sites were treated as site specific. Where there were human remains with no associated faunal baseline, the FRUITS models for these samples were considered on a case-by-case basis (see Chapter 6.4.1 and Table 6.3 below).

6.3.3 Summary of Mesolithic and Neolithic Faunal Samples

The $\delta^{15}N$ and $\delta^{13}C$ measurements of Mesolithic and Neolithic faunal bone collagen from Scotland were subjected to statistical testing. Two distinct baseline regions were identified: sites in Orkney and sites at the West coast. While the remains from the two sites in Orkney are isotopically comparable, Risga from the west coast has been identified as isotopically distinct from the other sites in that area. This information can be used to assign isotope values to be used as the terrestrial baseline for human dietary reconstruction using stable isotopes. The following section will deal with how these baselines have been assigned and the dietary estimates that result.

6.4 Human dietary reconstruction and radiocarbon age calibration

Questions that are addressed about human diet and chronology here are:

1. Considering all the information in sections 6.2 and 6.3, what is the appropriate dietary isotope baseline for all human samples considered in this thesis?
2. Using the FRUITS programme, what are the estimated dietary proportions of fish, shellfish and terrestrial mammal protein of the human individuals investigated within this study?
3. Considering the estimated abundance of marine resources in the diet of all sampled humans and the possible marine radiocarbon reservoir effects on each sample, what are the most accurate radiocarbon dates for the humans?
4. As a result of reconsidering the stable isotope and radiocarbon evidence in this thesis, what are the implications for dietary change during the Mesolithic-Neolithic transition?

6.4.1 Chosen faunal baselines for each human bone collagen sample

Following the detailed analysis of $\delta^{13}C$ and $\delta^{15}N$ measurements made on both modern and archaeological faunal samples, we can begin to build appropriate dietary baselines for each human sample in this study. Careful consideration has been taken when choosing these baselines to ensure that they are as representative as possible of the original human diet in both food group and isotopic composition. For each human sample, likely food sources have been identified from the published archaeological record and a baseline has been assigned, based on the modern and archaeological faunal values that best match these sources.

At some sites, bird bones were recovered during excavation; however, it was not possible to measure either ancient or modern bird bone collagen isotope values during this research. Birds are therefore not included as a food group in the FRUITS dietary reconstructions. Species such as gulls, razorbills and auks were occasionally reported however, these finds were rare and since seabirds have a diet of marine fish, their isotope values will be comparable to marine mammals which have been accounted for where present on a site, so it is very likely that this omission does not significantly affect the accuracy of the results.

It is also acknowledged that plants will have almost certainly been a contributor to the Mesolithic and Neolithic diet. These types of samples do not survive in a measurable state at archaeological sites, so it was hoped that modern plants such as grains and fruits would

be suitable for inclusion in the FRUITS dietary reconstructions. Unfortunately, the inclusion of modern plant samples as food groups in FRUITS was not possible because measured samples from the modern terrestrial environment were incomparable to ancient terrestrial equivalents (see sections 6.2.2 and 6.2.3). The exclusion of plants from the dietary reconstructions in this thesis does not affect the quality of the model though; the models consider the contribution of dietary protein only and since plants contain very little amounts of protein in relation to animal meat, the effects of the exclusion are negligible.

The varying nature of the locations (e.g. island vs. mainland) and the species of fauna contained at the sites necessitated the individual consideration of the samples that should be included as the dietary baseline in each of the FRUITS dietary reconstructions. Table 6.3 summarises all food isotopic baseline data included in each FRUITS model at each site, which is derived from the mean value of the food group isotope measurements at each site (see the individual site case studies in section 6.4.2 for details of how each individual food value was derived. Each bone collagen value has been converted to a dietary value using the tissue offsets defined in section 6.2.1 and modern samples have been corrected for the Suess Effect.

Table 6.3 $\delta^{13}C$ and $\delta^{15}N$ values with associated errors, used for food group values in FRUITS models for each site containing human remains.

		Food group $\delta^{13}C$ and $\delta^{15}N$ values (‰ ± SEM)			
Site		**Marine mammal**	**Marine fish**	**Marine shellfish**	**Terrestrial herbivore**
Carding Mill Bay	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-24.8±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	3.6±0.1
Cnoc Coig	$\delta^{13}C$	-15.6±0.7	-16.8±0.1	-15.0±0.1	N/A
	$\delta^{15}N$	15.9±0.1	12.9±0.3	8.8±0.1	
Crow Taing	$\delta^{13}C$	-16.3±0.1	-16.8±0.1	-15.0±0.1	-23.4±0.1
	$\delta^{15}N$	15.6±0.2	12.9±0.3	8.8±0.1	6.4±0.4
Embo	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.9±0.1

Site		Food group $\delta^{13}C$ and $\delta^{15}N$ values (‰ ± SEM)			
		Marine mammal	**Marine fish**	**Marine shellfish**	**Terrestrial herbivore**
	$\delta^{15}N$		12.9±0.3	8.8±0.1	4.9±0.2
Holm of Papa Westray	$\delta^{13}C$	-13.6±1.2	-16.8±0.1	-15.0±0.1	-23.9±0.1
	$\delta^{15}N$	16.5±0.6	12.9±0.3	8.8±0.1	4.9±0.2
Loch Borralie	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.9±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	4.9±0.2
Quoyness	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.4±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	6.4±0.4
Raschoille Cave	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-24.8±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	3.6±0.1
Tulach an t'Sionnach	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.9±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	4.9±0.2
Tulloch of Assery A	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.9±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	4.9±0.2
Tulluch of Assery B	$\delta^{13}C$	N/A	-16.8±0.1	-15.0±0.1	-23.9±0.1
	$\delta^{15}N$		12.9±0.3	8.8±0.1	4.9±0.2

6.4.2 Diet and chronology of humans at each site

In this section, each site is presented in chronological order as a case study. Crow Taing was identified as an outlier site following radiocarbon dating and is presented last, since it does not contribute towards the aims of this thesis. For every site analysed in this research, the chosen species that make up the isotope faunal baseline are defined and validated before the results of dietary modelling using stable isotope analysis and FRUITS is presented. Once the dietary habits for humans have been analysed, the radiocarbon dates for the human individuals were assessed to take into account new information about marine resource

consumption. The radiocarbon ages for all humans with ^{14}C measurements were calibrated using the IntCal13 and the Marine13 calibration curves in Oxcal 4.2 (Bronk-Ramsey, 2009; Reimer 2013). Marine dietary information derived from FRUITS was used, along with the appropriate ΔR value: for Cnoc Coig and Raschoille cave, this value is the Scottish west coast ΔR = -68 ± 90 ^{14}C yrs and for all other sites the value is the Scotland average ΔR = -47 ± 52 ^{14}C yrs, following Russell et al. (2015). For Carding Mill Bay, a new site-specific ΔR value (ΔR = -130 ± 34 ^{14}C yrs) was calculated, since questions arose regarding the validity of the existing values (Bownes et al., 2017). See Table 6.4 for the previously calculated ΔR values and Chapter 5.4.3 for the calculation of the new value. In each case, the findings relating to human diet and site chronology are placed within the wider context of the available published literature concerning dietary patterns and the site and/or relationships between the site and different regions and time periods.

Table 6.4 ΔR values for Carding Mill Bay from literature sources and this study

Context #	ΔR Value	Source
XIII	+150 ± 28	Ascough et al. (2007)
XIV	-44 ± 91	Reimer, et al, (2002)
XIV	-130 ± 34	This research
XV	+86 ± 67	Reimer, et al, (2002)

Cnoc Coig (and a comment on Caisteal Nan Gillean II)

At the midden site of Cnoc Coig (6500 to 3800 BC), bird and mammal bone was recorded, however no faunal remains are stored by National Museums Scotland for sampling, so the terrestrial baseline was selected from the best fitting samples as follows: the species of fauna that were present at Cnoc Coig were noted and samples of the same species were sought from appropriate collections. Fish and shellfish remains were abundant on the site and were included as two food groups in the FRUITS reconstructions of human diet; the values for these food groups were derived from the measurements of the modern fish and shellfish analogues. Mammal bone was scarce at Cnoc Coig but included otter, seal, pig and red deer. However, very few of the terrestrial bones were meat-bearing skeletal elements (e.g. upper

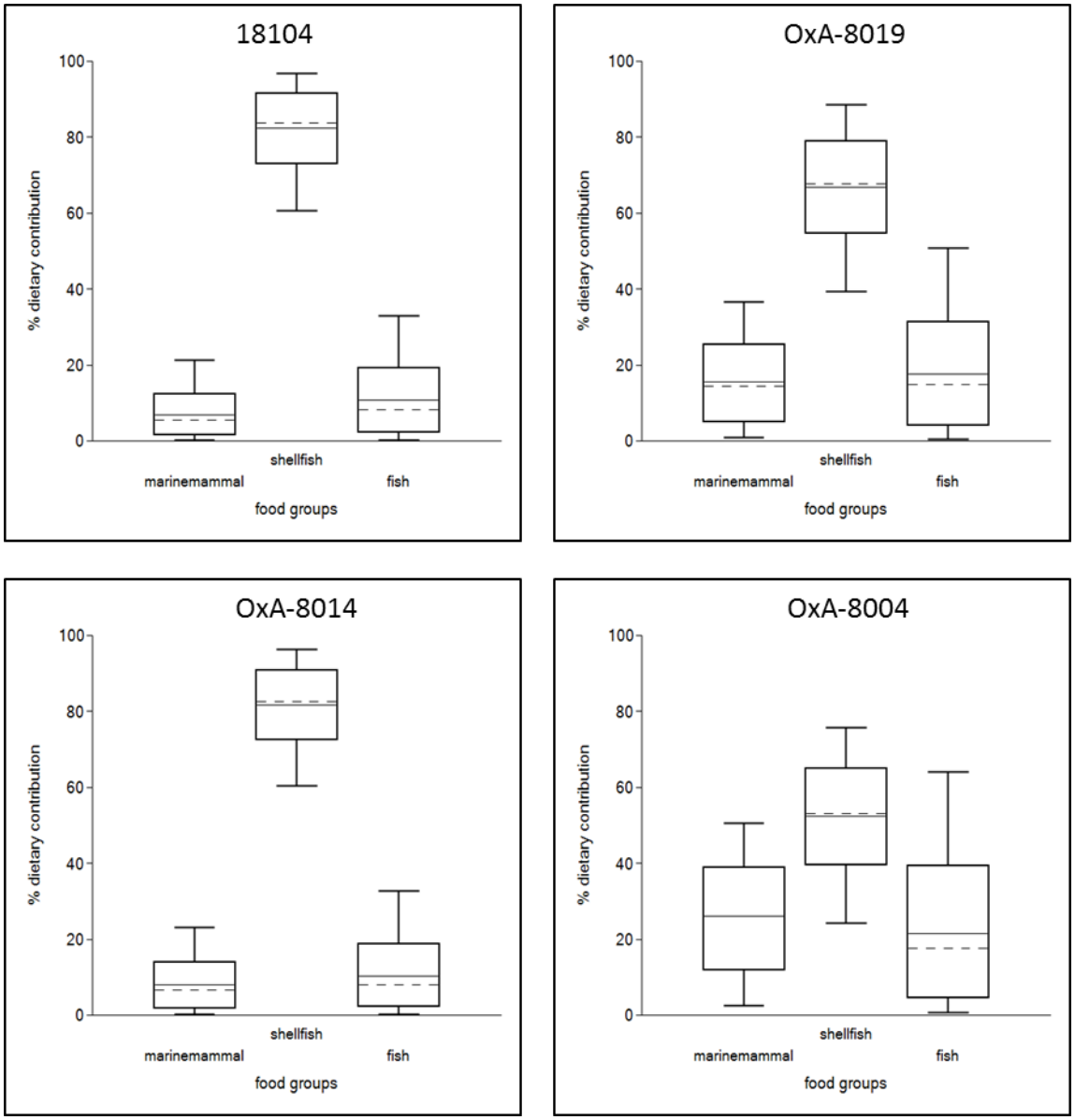
leg joints), suggesting that red deer and pig bones were used for making tools and were not consumed (Richards and Mellars, 1998). Due to the likely absence of terrestrial mammals in the diet as demonstrated by the archaeological evidence, this group was not included in the FRUITS models for human diet at this site. Instead, an average value taken from a seal bone and an otter bone from Sanday was used to form the food group 'marine mammals'. It was felt that this would give the best representation of dietary baseline values for Cnoc Coig; however, caution must be exercised when judging the accuracy of the FRUITS dietary reconstructions at this site since this food group is derived from non-local samples from over 250 miles away. A large amount of fish and shellfish remains were present at the site: saithe, ballan wrasse, thornback ray, small spotted dogfish, ling, a possible salmonid, limpet, winkle, cockle, whelk, oyster, razor shells, crab and lobster (Richards and Mellars, 1998). All fish and shellfish measured in this study were therefore utilised in the fish and shellfish baseline at Cnoc Coig. This resulted in the FRUITS models for this site recreating a 100% marine diet for all humans. The focus of the investigation for this site, in addition to providing an accurate dietary reconstruction of humans at the site, was to evaluate whether FRUITS was capable of distinguishing between three different marine food groups: mammals, shellfish and fish.

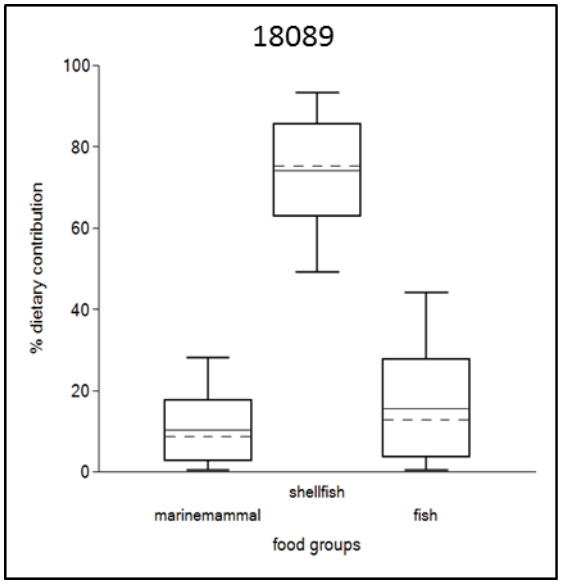
Dietary reconstructions were created for seven humans from Cnoc Coig. Five of the individuals had previously been analysed by Schulting and Richards (2002) using stable isotopes and radiocarbon dating, three of these individuals' measurements were originally published in Richards and Sheridan (2000). Two new sets of isotope and radiocarbon data were produced from two individuals supplied by National Museums Scotland. See Table 6.4 for a summary of the stable isotope and radiocarbon date.

Table 6.4 Summary information for human bone collagen samples from Cnoc Coig, including stable carbon and nitrogen isotope values and radiocarbon measurements. Context information was unavailable for some samples and is recorded as N/A in each case.

Source	**Sample ID**	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
This thesis	GU41836	N/A	-12.8	16.6	3.3	5492±36
This thesis	GU40827	N/A	-13.1	16.1	3.4	5619±31
Schulting and Richards (2002)	18104	N/A	-13.2	14.5	3.1	N/A
Schulting and Richards (2002) after Richards and Sheridan (2000)	OxA-8019 (17157)	Square H13, Unit 4	-12.3	16.0	3.1	5615±45
Schulting and Richards (2002) after Richards and Sheridan (2000)	OxA-8014 (17203)	Square I13, Unit 4	-12.0	14.7	2.9	5495±55
Schulting and Richards (2002) after Richards and Sheridan (2000)	OxA-8004 (18284)	Square I5, Unit 4	-12.0	17.0	3.1	5740±65
Schulting and Richards (2002)	18089	N/A	-13.6	15.2	3.1	N/A

Figure 6.5 FRUITS reconstruction of individuals from Cnoc Coig. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

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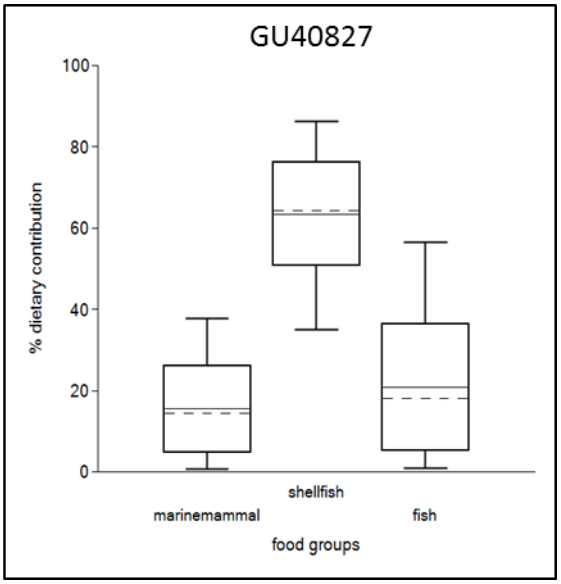
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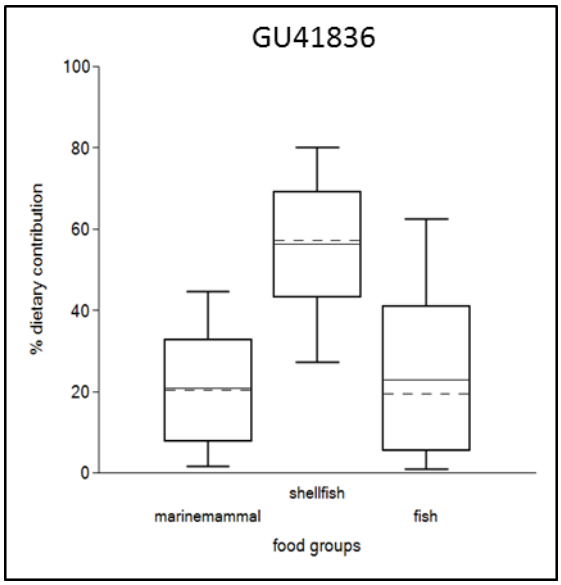
GU41836
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% dietary contribution
shellfish
marinemammal
fish
food groups

Table 6.5 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for all humans at Cnoc Coig

Sample ID	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**
18104	7±6	11±9	82±9
OxA-8019	16±10	18±14	67±12
OxA-8014	8±6	10±9	82±9
OxA-8004	26±13	22±17	52±13
18089	10±8	16±12	74±11
GU41836	21±12	23±17	56±13
GU40827	16±10	21±15	63±13

There are some unique issues to consider when analysing the dietary reconstructions for the humans at Cnoc Coig. While each FRUITS model successfully converged and produced results that estimated the dietary contribution of three marine food groups (see Figure 6.5), the precision of the results is not ideal. One of the major advantages of FRUITS is its ability to apply mathematical uncertainties to dietary estimates, in comparison to linear interpolation which does not (see Chapter 3.3 for a review of FRUITS and linear interpolation as dietary reconstruction tools). In the case of linear interpolation, the uncertainity associated with deriving marine resources in the diet is ±10%, given that $\delta^{13}C$ values vary by approximately 1‰ due to analytical machine error and natural intra-sample variation (Ascough et al., 2012). The uncertainity associated with food group contributions to diets in the majority of individuals at Cnoc Coig exceeds this, with some estimates showing an uncertainty of up to 13% (see Table 6.5). It is possible to use the addition of Bayesian priors in FRUITS to attempt to mitigate results such as these (Fernandes et al., 2014). However, *a priori* information was not applied to the models for Cnoc Coig, given that it was not possible to make any prior assumptions about diet that extended any further than those already applied when selecting the isotopic dietary baseline. While these relatively large uncertainties do not undermine the accuracy of the model, Fernandes has

cautioned against making definitive interpretation of FRUITS data with these relatively high degrees of statistical uncertainty (Fernandes et al., 2015).

Despite concerns about precision, these dietary reconstructions for Cnoc Coig do have some strengths in comparison to other published estimates. Schulting and Richards (2002) used linear interpolation to estimate diet at Cnoc Coig. They used the accepted general dietary endpoints of -12‰ for a 100% marine diet and -21‰ for a 100% terrestrial diet to estimate that these individuals sourced 82-100% of their diet from marine environment. They did not; however, consider the *a priori* evidence of diet from the faunal remains at Cnoc Coig: the current understanding from the literature is that the terrestrial herbivores that were present were not consumed as part of the diet (Richards and Mellars, 1998). We can assume that only marine protein was consumed at the site, and the application of linear interpolation by Schulting and Richards (2002) may be considered unnecessary as the total diet was not comprised of a mixture of marine and terrestrial resources. Having said this, it is acknowledged that their approach utilised the best methods available at the time. When considering the new isotope values and reconsidering previous values, FRUITS is a good choice to model diet at Cnoc Coig since the program can differentiate between different food groups from the same environment. It could be argued that the dietary reconstructions presented here are more meaningful because they consider the different food consumed as indicated by the archaeological evidence.

Table 6.6 Summary of calibrated radiocarbon dates of humans from Cnoc Coig. Samples prefixed with 'GU' are new measurements reported with 95% confidence interval, samples prefixed with 'OxA' are measurements from Richards and Sheridan (2000) and are rounded up to the nearest century.

Sample ID	**Radiocarbon age (BP)**	**Calibrated age range (cal BC)**
GU41836	5492±36	4236-3769
GU40827	5619±31	4333-3943
OxA-8019	5615±45	4200-4000
OxA-8014	5495±55	4000-3800
OxA-8004	5740±55	4200-4000

Figure 6.6 Radiocarbon dates of humans from Cnoc Coig using the Marine13 calibration curve and a ΔR value of -68 ± 90 ^{14}C yrs (Richards and Sheridan, 2000)

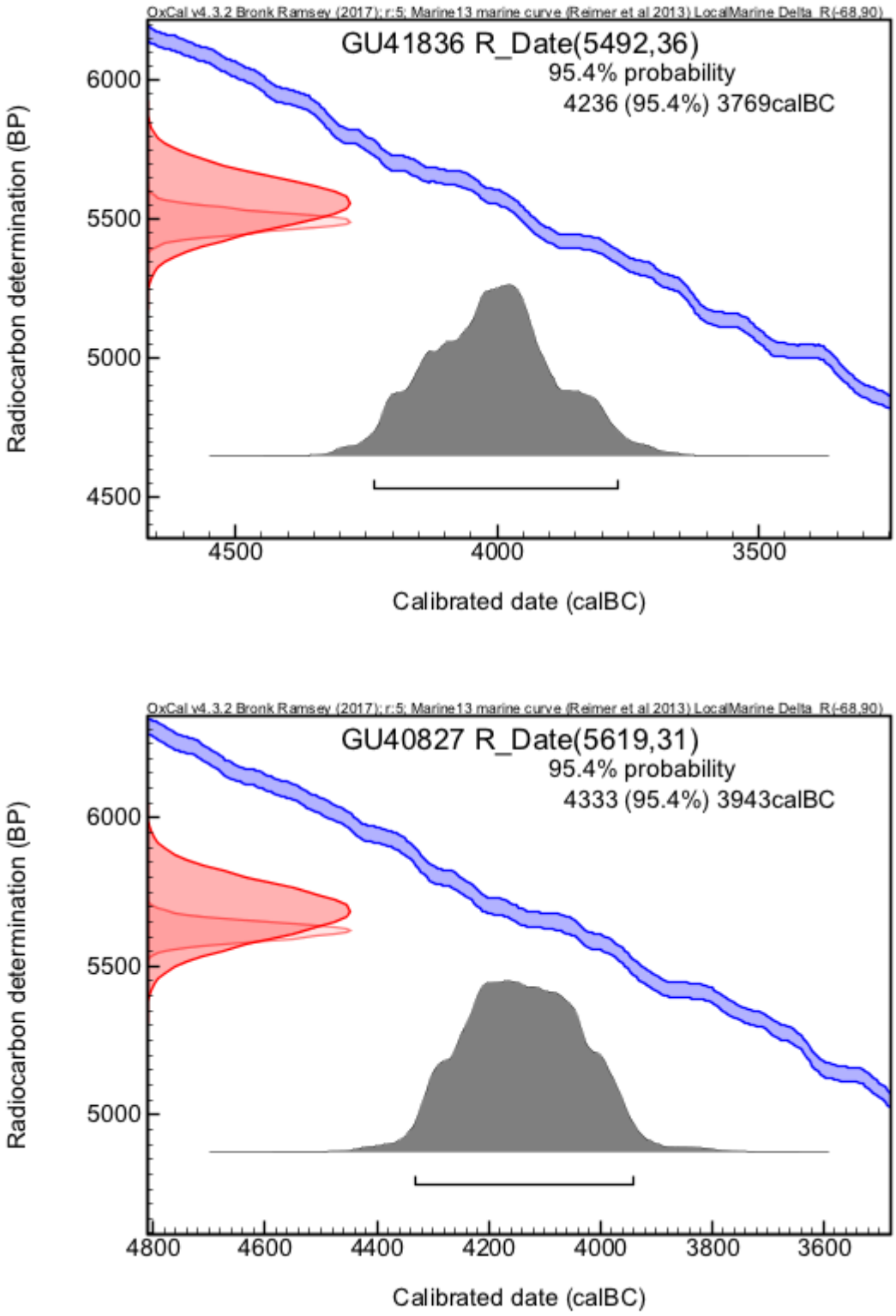


Table 6.6 and Figure 6.6 show the new radiocarbon dates for human bone collagen samples from Cnoc Coig, placing them both within the Mesolithic period. There was no need to initially calibrate the dates using the Intcal13 curve and then recalibrate them using a mixed marine/terrestrial curve (as was the case at all other sites considered here) since it is already acknowledged in the literature that these individuals will display a MRE due to marine carbon in the bone collagen. The results from Cnoc Coig provide us with evidence to support the consumption of a typical Mesolithic diet, rich in marine resources and, being the oldest site in this research, provides a chronological 'bookend' to which the diets of more recent individuals can be compared (see figure 6.23).

A comment on Caisteal Nan Gillean

Caisteal Nan Gillean is a shell midden dating 5300 to 2600 BC. The new dates from Cnoc Coig presented in this thesis overlap with dates published in Richards and Sheridan (2000), who argued that the late Mesolithic was contemporary with the early Neolithic in Scotland. This argument requires re-evaluating since the dates for the Mesolithic site (Caisteal Nan Gillean II) in Richards and Sheridan (2000) were roughly calculated using carbon isotopes as the only dietary proxy (see Table 6.7 for isotope values). While the Cnoc Coig ages were relatively easy to calculate using the marine calibration curve, the Caisteal Nan Gillean II sample showed evidence of a mixed marine/terrestrial diet (Richards and Sheridan, 2000). This sample was treated by Richards and Sheridan as follows: it was estimated that there was a 50% marine protein contribution to diet based on the fact that the $\delta^{13}C$ value of the individuals (-16‰) is roughly equidistant between the dietary end member of -12 and -21‰. The date of the human individual was calculated by taking the midpoint between the date generated using the marine curve and the date from the terrestrial curve (i.e. not by using mixed marine/terrestrial modelling in Oxcal) and with no reference to the ΔR values for Scotland (Richards and Sheridan, 2000). The resulting dates for both the sites in the paper was rounded to the nearest 100 years (see Table 6.6), adding further conjecture to their assumptions. Since both the dietary estimate and the date for sample OxA-8005 was questionable, the stable isotope and radiocarbon data were re-evaluated in this study using FRUITS and OxCal 4.2 (Bronk Ramsey, 2009).

Table 6.7 Summary information for the human sample from Caisteal Nan Gillean II, including stable carbon isotope values and radiocarbon measurements. Data sourced from Richards and Sheridan (2000).

Sample ID	**Site name**	**Context**	**$\delta^{13}C$ ‰**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
OxA-8005	Caisteal Nan Gillean II	Trench P/N, Layer 1/2, Unit 4	-16.0	5480±55

Figure 6.7 FRUITS reconstruction of the individual OxA-8005 from Caisteal Nan Gillean II, from Richards and Sheridan (2000). Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

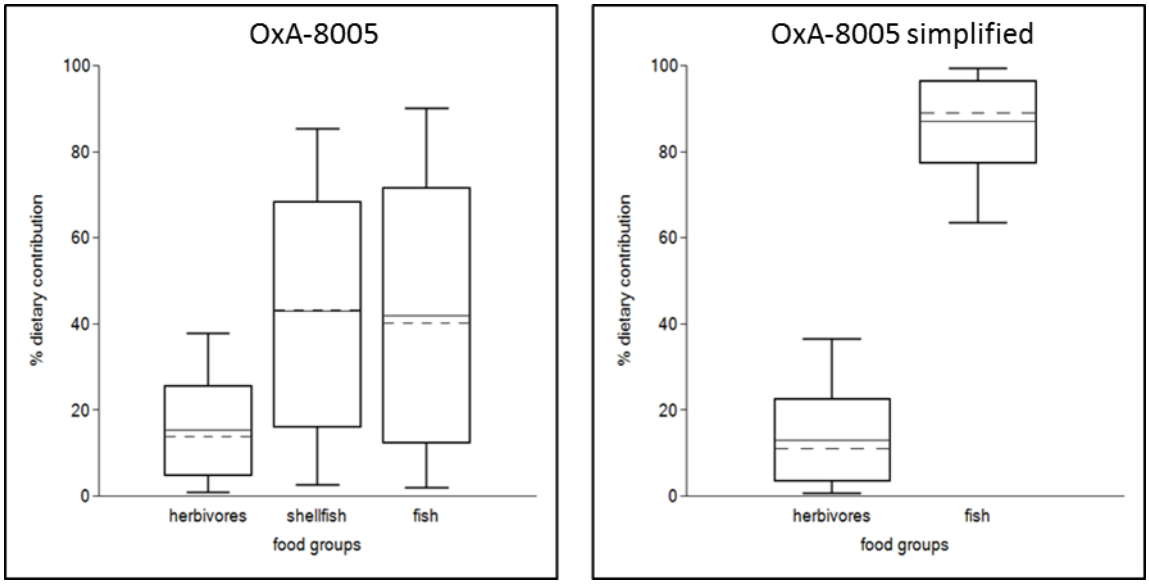


Table 6.8 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for the human at Caisteal Nan Gillean II

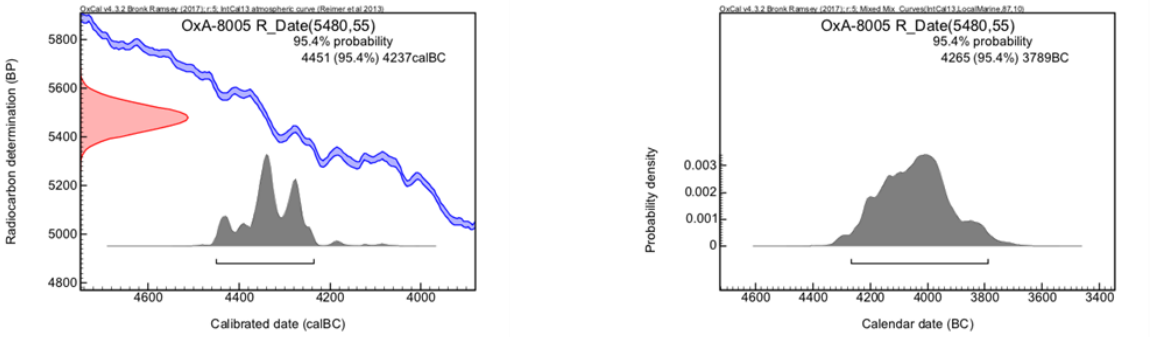
Sample ID	**Site name**	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
OxA-8005	Caisteal Nan Gillean II	N/A	42±26	43±24	15±10
OxA-8005 simplified	Caisteal Nan Gillean II	N/A	87±10	N/A	13±10

Although the FRUITS model fully converged, the initial estimation of the abundance of fish and shellfish protein in the diet for the individual at Caisteal Nan Gillean II was very imprecise (±26% and ±24% respectively). This is very likely because there was only one isotopic proxy measurement, $\delta^{13}C$, available for use in FRUITS. Using more than one dietary proxy when modelling ancient diet means that the model is able to better distinguish between the isotopic characteristics of the different food sources and therefore ascribe more precision to their relative contribution to the target. In the case of Caisteal Nan Gillean II, FRUITS could not give the high precision seen in other models in this research, and so amendments were made to the model to compensate for the reduced amount of input data.

When the FRUITS model was simplified to include two food groups instead of three, (fish and terrestrial herbivores), better precision was achieved for the dietary estimates (see Figure 6.7 and Table 6.8). The simplified model attributed a 10% uncertainty to both food groups, which is acceptable according to Fernandes et al. (2014). Remarkably, in both the simplified model and the initial model, the estimation of terrestrial protein in the diet was far lower than that estimated by Richards and Sheridan (2000). While the FRUITS model cannot be argued to be as reliable as those that use both carbon and nitrogen stable isotope data, it can be assumed to be more reliable than the dietary reconstruction proposed by Richards and Sheridan (2000). Since the new estimation is calculated using appropriate tools and data, this

called the original diet and dating information into question, and a re-evaluation of the date of the sample at Caisteal Nan Gillean II was required.

Figure 6.8 Recalibrated radiocarbon dates of individual OxA-8005 from Caisteal Nan Gillean using a ΔR value of -68±90 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. The date on the left has been calibrated using the terrestrial IntCal13 curve. The date on the right has been calibrated using the mixed marine/terrestrial curve



To re-interpret the date for OxA-8005 from Caisteal Nan Gillean II, the original radiocarbon age was calibrated using the terrestrial IntCal13 calibration curve and then recalibrated using the mixed marine/terrestrial curve, dietary information from FRUITS and the mean ΔR value for the west coast of Scotland of -68±90 ^{14}C yrs (Russell et al., 2015). After taking this new information into account, the radiocarbon age for OxA-8005 that accounts for marine carbon in the sample shifts from 4200 to 4000 cal BC, originally estimated by Richards and Sheridan (2002), to 4265 to 3789 BC. This updated date is less precise, yet it is likely to be more accurate than the date derived by Richards and Sheridan (2000) because it took into account geographically and time appropriate ΔR value and used the mixed marine/terrestrial calibration curve to generate the age.

Interestingly, the new date for this human individual is considerably younger than originally calculated, dating the sample to the Mesolithic-Neolithic transition, not the late Mesolithic as previously thought. This therefore strengthens their argument which used this sample to suggest that the Mesolithic overlapped with the Neolithic in Scotland (Richards and Sheridan, 2000). It was argued that the late Mesolithic radiocarbon date showed that the

marine resources were being exploited at the midden at the same time as farming was being established. Other studies have presented similar findings in Scotland, with incremental isotope analysis backing the hypothesis that Neolithic people periodically returned to marine resources (Montgomery et al., 2013), and archaeological evidence in the form of marine fish and shellfish remains supporting the idea that marine foods were consumed in the Neolithic period (Milner et al., 2004). The new radiocarbon date for Casteal Nan Gillean presented in this thesis places the use of marine resources at the site to later than the end of the Mesolithic period, and further implies that the dietary changes during the Mesolithic-Neolithic transition were gradual, instead of being a sharp change.

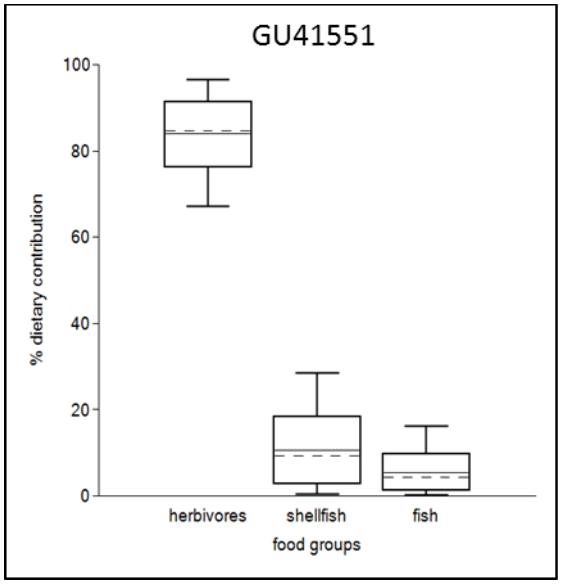
Tulach an t'Sionnach and the Tullochs of Assery

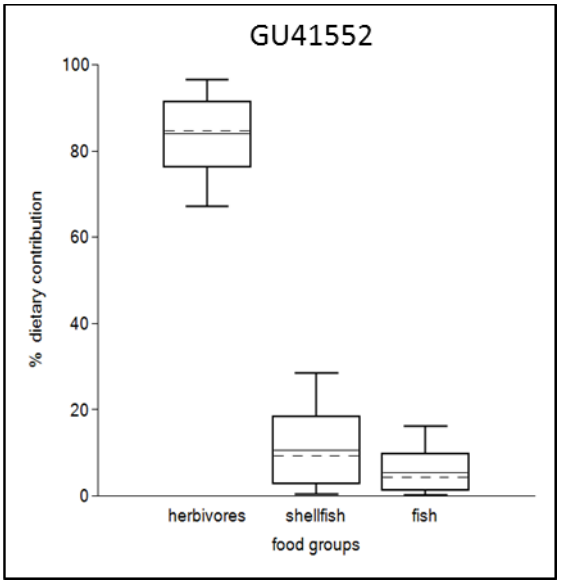
The cairns of Tulach an t'Sionnach, Tulloch of Assery A and Tulloch of Assery B are located very close to each other (approximately 700 metres apart) and are therefore treated as one site in Caithness, north Scotland (See Table 6.9 for summary information). No faunal remains were present at Tulloch of Assery A; however, Tulach an t'Sionnach contained limpets, land snails and other molluscs, cattle, red deer and possible bird and fish remains, and Tulloch of Assery B contained cattle, red deer, pig, possible sheep, unidentified bone fragments and two types of bird (Corcoran, 1964). The baselines assigned to the human individuals from these three chambered cairns are an average value of all archaeological terrestrial herbivores in Scotland, all species of fish and all species of shellfish considered in this study. Since no site-specific isotope baseline could be assigned, the next best baseline was country-specific.

Table 6.9 Summary information for human bone collagen samples from Tulach an t'Sionnach and the Tulloch of Assery A and B, including stable carbon and nitrogen isotope values and radiocarbon measurements. Context information was unavailable for some samples and is recorded as N/A (not available) in each case.

Sample ID	**Site name**	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
GU41551	Tulach an t'Sionnach	N/A	-21.1	10.1	3.3	4851±34
GU41552	Tulloch of Assery A	LC/TAA/25b- 10	-21.1	10.1	3.2	4796±37
GU41550	Tulloch of Assery B	LC/TAB/58	-21.6	9.8	3.1	4911±32

Figure 6.9 FRUITS reconstructions of individuals from the Tulach an' tSionnach and the Tulloch of Assery A and B. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean





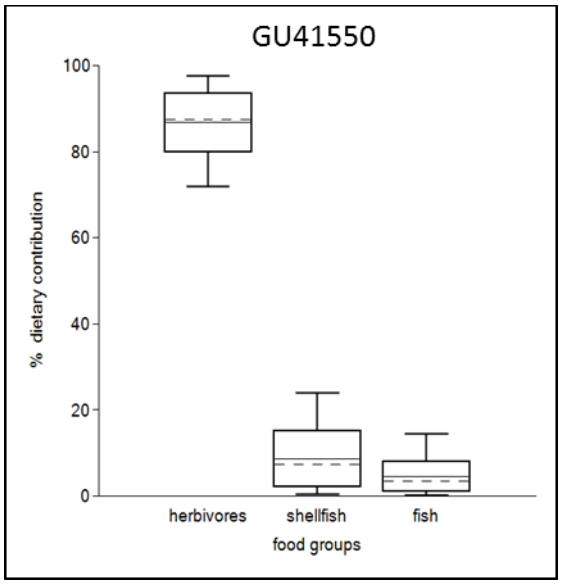


Table 6.10 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for humans from Tulach an t'Sionnach and the Tulloch of Assery A and B.

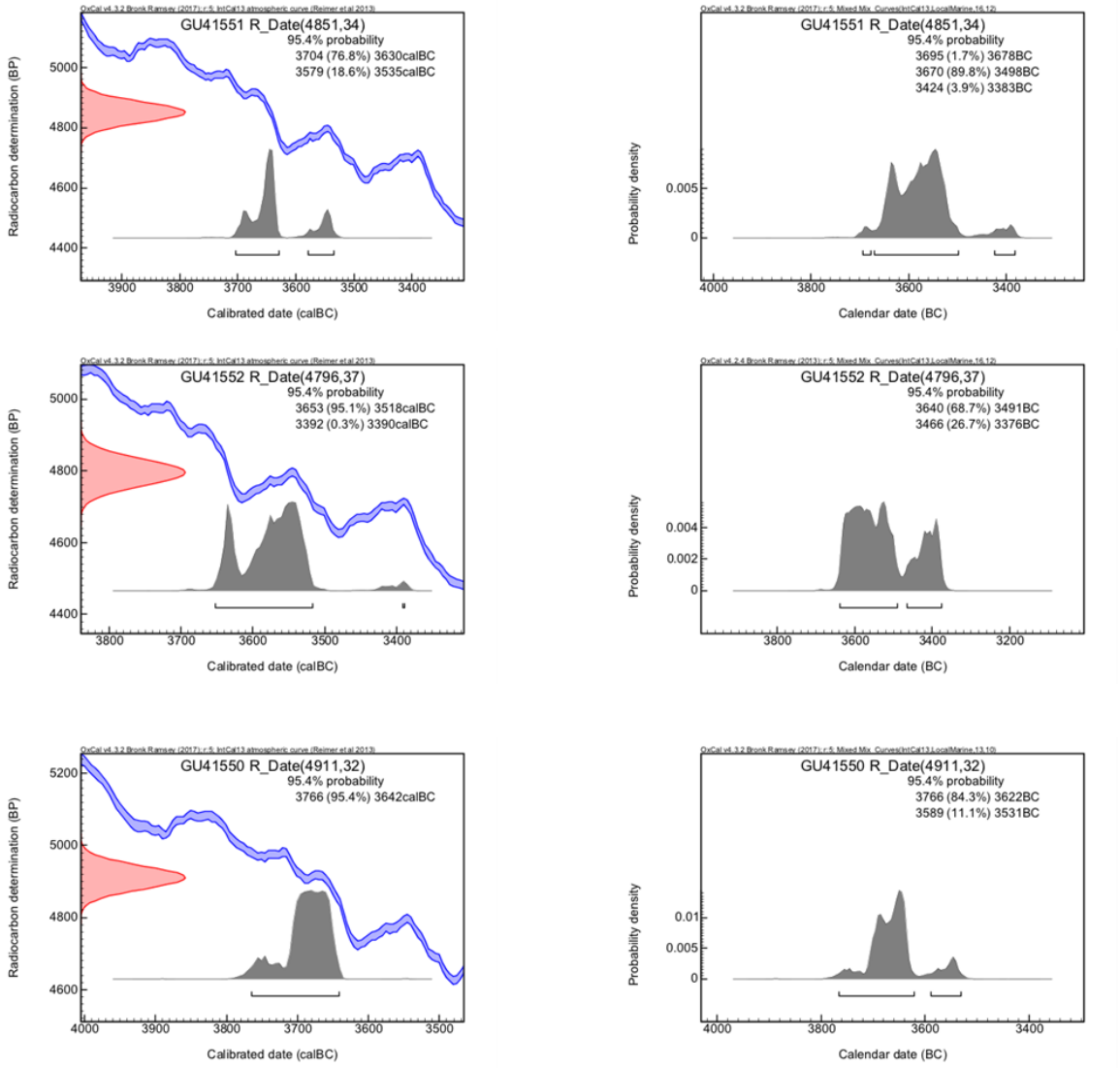
Sample ID	**Site name**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
GU41551	Tulach an t'Sionnach	5±4	11±8	84±8
GU41552	Tulloch of Assery A	5±4	11±8	84±8
GU41550	Tulloch of Assery B	4±4	9±6	87±7

The FRUITS dietary reconstructions of the three human individuals, one sample from each tomb, suggested that marine resources, shellfish in particular, were still an important part of the diet in the Scottish Neolithic (see Table 6.10 and Figure 6.9). Interestingly, there is a striking consistency of diet between the three individuals. Each human derived c.5% of their dietary protein from fish, c.10% from shellfish and the rest from terrestrial herbivores. This implies that there were no age/gender or status related differences in their lifestyles. The individuals from Tulach an t'Sionnach and the Tulloch of Assery A and B shared the same dietary characteristics as those from Carding Mill Bay, Embo, the Holm of Papa Westray and Raschoille cave (these sites are examined below).

Table 6.11 Summary of recalibrated radiocarbon dates of humans from Tulach an' tSionnach and the Tulloch of Assery A and B. Calibrated age ranges calculated using the terrestrial IntCal13 curve. Recalibrated ages calculated using the mixed marine-terrestrial curve, a ΔR value of -47 ± 52 ^{14}C yrs and dietary estimates derived using FRUITS. Reported with 95% confidence interval.

Sample ID	Radiocarbon age (BP)	Calibrated age range (cal BC)	Recalibrated age range (cal BC)
GU41551	4851±34	3704-3535	3695-3383
GU41552	4796±37	3653-3390	3640-3376
GU41550	4911±32	3766-3642	3766-3531

Figure 6.10 Recalibrated radiocarbon dates of humans from Tulach an' tSionnach and the Tulloch of Assery A and B using a ΔR value of -47 ± 52 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Dates on the left have been calibrated using the terrestrial IntCal13 curve. Dates on the right have been calibrated using the mixed marine/terrestrial curve



The recalibrated dates for the human remains from each tomb (|Figure 6.10) spanned the period 3766 to 3376 BC, covering the time between the Mesolithic-Neolithic transition to the early Neolithic. All radiocarbon recalibrations became less precise than the original calculation, but by taking into account marine carbon in the samples the dates are more likely to encompass the true age of the sample. The three tombs have been the subject of a detailed past radiocarbon study which aimed to explore the relationships between each tomb (Sharples, 1986). In this study, Sharples concluded that the tombs were chronologically

connected, with all three being built within 200 years (Sharples, 1986). Indeed, the dates were too close to establish a reliable sequence of construction (see Table 6.11 and Figure 6.10). It is unfortunate that the new dates generated in this research are unable to contribute to this argument since all three coincide with each other even before they are recalibrated. This point reinforces the importance of the method of recalibration adopted in this research in order to obtain accurate radiocarbon dates. To confidently assign a sequence to these, or any other, connected sites, it is essential that the dates are distinct following appropriate assessment of possible marine reservoir effects. In the case of Tulach an t'Sionnach and the Tulloch of Assery A and B, the radiocarbon dates for each human sample overlap and are not distinct from each other.

Loch Borralie

Human remains from Loch Borralie were the most problematic to confidently assign isotope dietary baseline values to (see Table 6.12 for summary stable isotope and radiocarbon data for the two bone collagen samples). The site was an un-stratified cave with the only associated animal remains being from carnivores. Adding to the uncertainty of stable isotope interpretations because of the lack of faunal remains was the location of the site: Loch Borralie is in north mainland Scotland, distinct from the two concentrations of sites in this study – Orkney and west coast mainland Scotland. The terrestrial baseline for Loch Borralie was therefore derived from an average value of all archaeological terrestrial herbivore isotope measurements in this study. It would have been inaccurate to assign a local baseline from another site in for Loch Borralie because isotope values can vary between sites. Instead, a 'Scottish' baseline ensured that the best matching baseline values were represented without being overly precise. The marine fish and shellfish baseline included all measured species. For this site, the food groups included in FRUITS were terrestrial herbivores, fish and shellfish, given that these are the most common combination of food groups for humans observed in this research. When interpreting the diets, it was not possible to assign a high level of confidence to the results; however, they did provide an indication of the most likely human dietary patterns.

Table 6.12 Summary information for human bone collagen samples from Loch Borralie, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements. Context information was unavailable for both samples and is recorded as N/A in each case.

Sample ID	**Site name**	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
GU36228	Loch Borralie	N/A	-20.7	9.3	3.3	4743±31
GU36229	Loch Borralie	N/A	-19.7	9.7	3.3	4875±32

Figure 6.11 FRUITS reconstructions of dietary reconstructions for individuals GU36228 and GU36229 from Loch Borralie. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

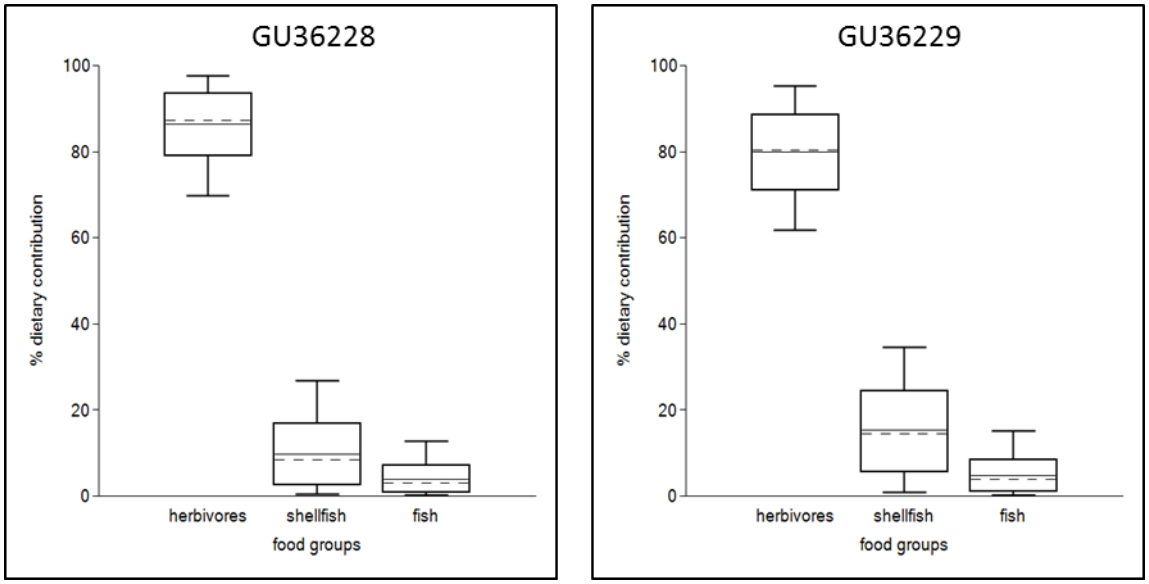


Table 6.13 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for human bone collagen samples from Loch Borralie.

Sample ID	**Site name**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
GU36228	Loch Borralie	4±3	10±7	86±7
GU36229	Loch Borralie	5±4	15±9	80±9

The results of the FRUITS dietary reconstructions for the samples from Loch Borralie indicate that the majority of the dietary protein in each case was sourced from the terrestrial environment (see Table 6.13). Between c. 14 ± 10% and 20 ± 19% of the diet was derived from marine sources. These dietary patterns are very similar to those seen in Neolithic sites in the West coast an Orkney (e.g. Raschoille Cave and the Holm of Papa Westray). While interpretation of the findings at Loch Borralie regarding diet must be cautious, as previously indicated, it is interesting that the 'standard' Neolithic diet, which is made up of terrestrial resources and a small amount of marine fish and shellfish, that was observed in the two main site areas of the west coast and Orkney are replicated here on the distant north mainland coast. This might indicate that the dietary patterns seen within the two larger site areas may be representative of the typical diet across the whole of Scotland during the Neolithic period.

The radiocarbon results for humans at Loch Borralie (Table 6.14 and Figure 6.12) did not follow the pattern seen in the dates from all other archaeological sites in this thesis that have been recalibrated to take into account some marine input into the diet. The trend seen at other sites was that taking into account the estimation of marine resources in the diet and calibrating the dates using a mixed marine/terrestrial calibration curve resulted in less precise dates compared to those calibrated using the terrestrial IntCal13 calibration curve alone. This is expected since the calculation of ages using the mixed calibration curve has more associated mathematical uncertainty because of the inclusion of errors associated with the ΔR value and the estimation of marine carbon in the sample. In addition, a larger error is associated with mixed samples because the marine curve is a model based on the terrestrial

data which reflects the smoothed response of the oceans to relatively rapid fluctuations in atmospheric ^{14}C. The ages at Loch Borralie, though, became slightly more precise when recalibrated using the mixed marine/terrestrial curve. This is most likely because the original cal BC ages fall on a 'flat' part of the calibration curve, resulting in a large estimated date range. The recalibration shifts the ages to intersect with a steeper part of the curve, resulting in more precise date ranges. However, the recalibration does not make a substantial difference to the age ranges of these samples.

Figure 6.12 Recalibrated radiocarbon dates of humans from Loch Borralie using a ΔR value of -47 ± 52 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Dates on the left have been calibrated using the terrestrial IntCal13 curve. Dates on the right have been calibrated using the mixed marine/terrestrial curve

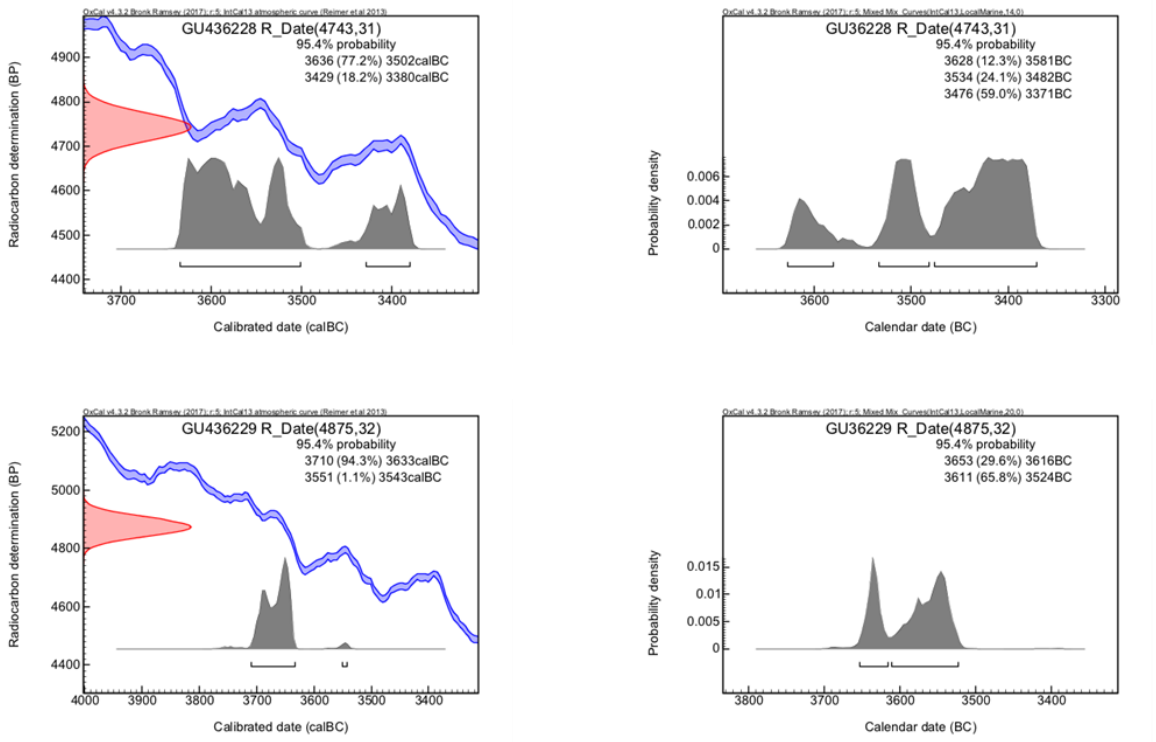


Table 6.14 Summary of recalibrated radiocarbon dates of humans from Loch Borralie. Calibrated age ranges calculated using the terrestrial IntCal13 curve. Recalibrated ages calculated using the mixed marine-terrestrial curve, a ΔR value of -47 ± 52 ^{14}C yrs and dietary estimations derived using FRUITS. Reported with 95% confidence interval

Sample ID	**Radiocarbon age (BP)**	**Calibrated age range (cal BC)**	**Recalibrated age range (cal BC)**
GU36228	4743±31	3636-3380	3628-3371
GU36229	4875±32	3710-3543	3653-3524

The recalibrated ages of the two human bone collagen samples from Loch Borralie are extremely close (see Table 6.14), as are the stable carbon and nitrogen isotope values (see Table 6.12). The similarity in the diet and dating information suggests that there may only be one individual present at the site: the human remains may represent a single isolated bone deposit, rather than a pair of individuals. The two skeletal element sampled were a humerus and a clavical, so it is not possible to be certain that they are from more than one individual. Nevertheless, the remains are interesting in that they date the early to mid-Neolithic. The unique nature of Loch Borralie (human remains that were discovered alongside much later carnivore remains) makes the cave worthy of further archaeological investigation. This is especially pertinent, given that there are currently no publications that record the site or its contents.

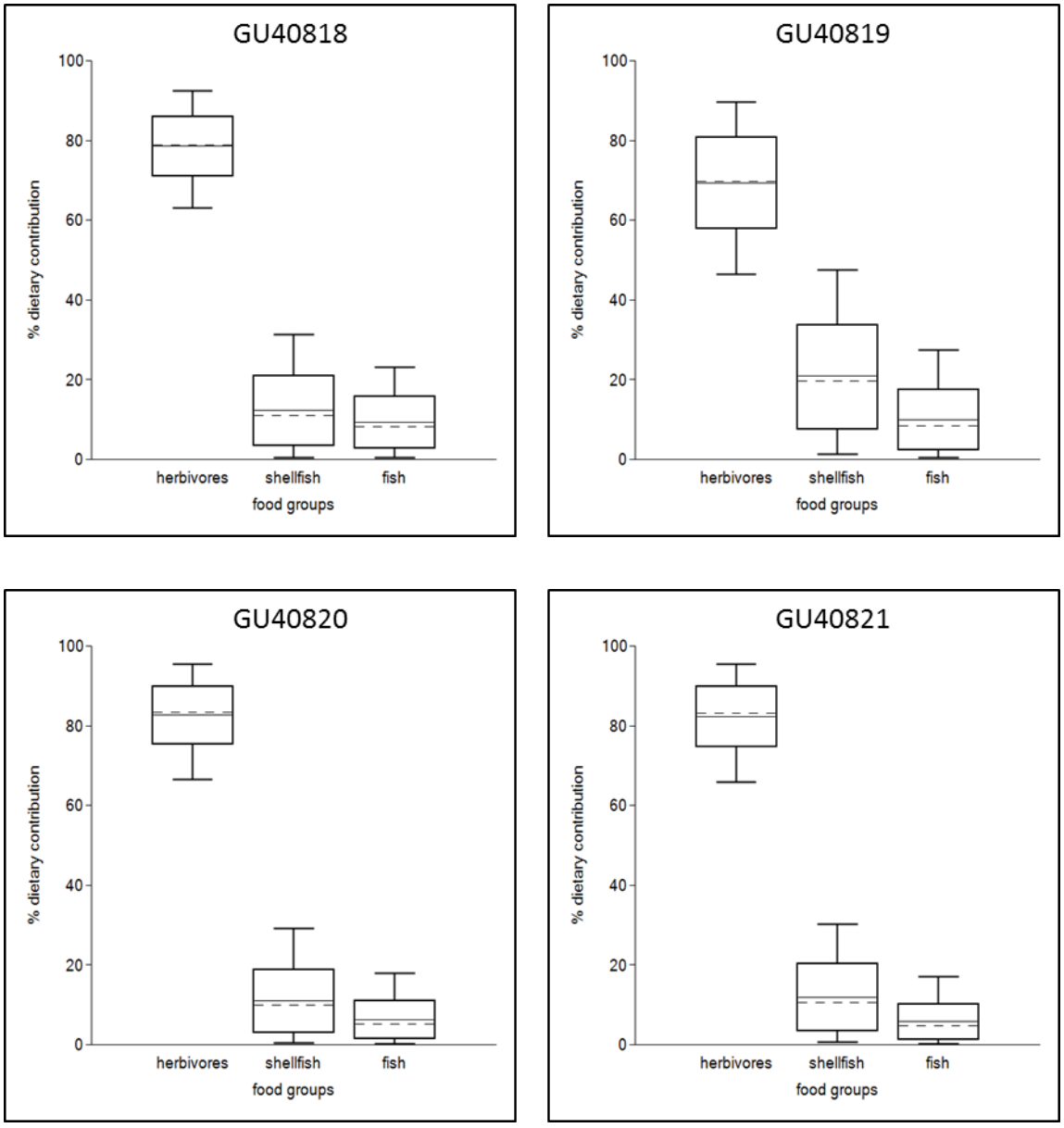
Raschoille Cave

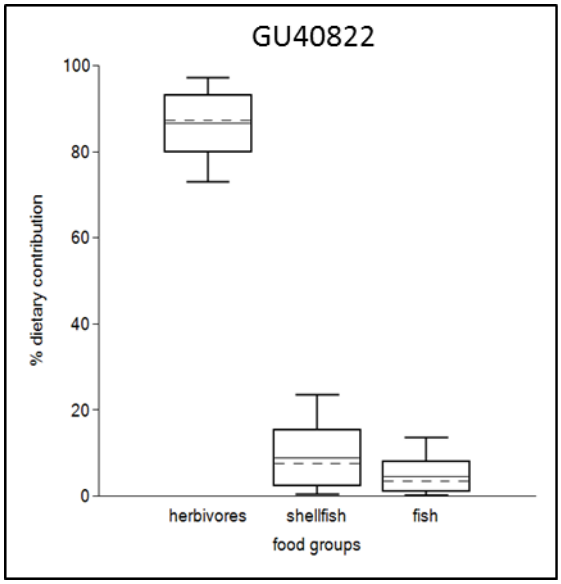
Nine Mesolithic human bone collagen samples from coastal site of Raschoille cave were analysed using stable isotope analysis and radiocarbon dating (see Table 6.15). Red deer remains were recorded as abundant at the site, but were unavailable for sampling (Connock, 1984, Connock, 1985). The close proximity of Raschoille cave to Carding Mill Bay; however, makes the terrestrial baseline from the latter site suitable as a replacement source of baseline samples (see Figure 4.2). A large amount of unspecified fish bones and shellfish were also recovered at Rashoille cave (Connock, 1984, Connock, 1985), so all available fish and shellfish species were assigned as food groups for the FRUITS models.

Table 6.15 Summary information for human bone collagen samples from Raschoille Cave, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements.

Sample ID	**Site name**	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
GU40818	Raschoille cave	ORC III 13.18	-21.9	8.4	3.5	4550±29
GU40819	Raschoille cave	ORC III 15.13	-21.7	7.7	3.3	4738±31
GU40820	Raschoille cave	ORC IV 34.8	-21.6	7.7	3.3	4817±31
GU40821	Raschoille cave	ORC II 95.2	-22.1	8.8	3.3	4490±29
GU40822	Raschoille cave	ORC III 12.10	-21.5	9.2	3.3	4499±29
GU40823	Raschoille cave	ORC I 2	-21.9	9.5	3.3	4668±29
GU40824	Raschoille cave	ORC I 2	-22.3	10.2	3.2	4432±31
GU40825	Raschoille cave	ORC I 2	-22.4	10.4	3.3	4731±29
GU40826	Raschoille cave	ORC III 31.32	-22.2	9.3	3.3	4638±31

Figure 6.13 FRUITS reconstructions of individuals from Raschoille Cave. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean




GU40822
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shellfish
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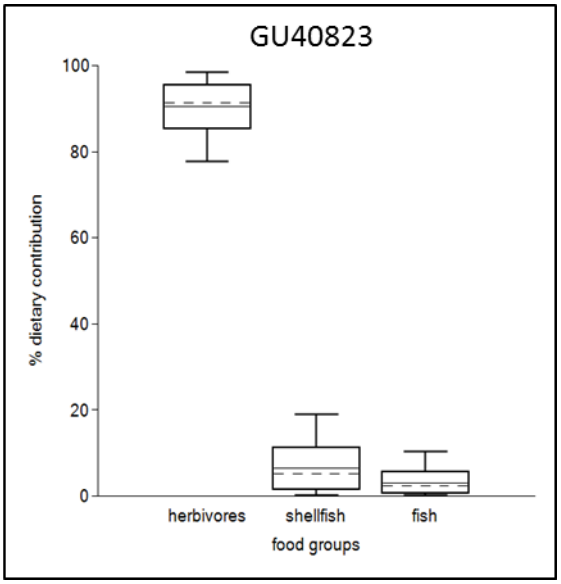
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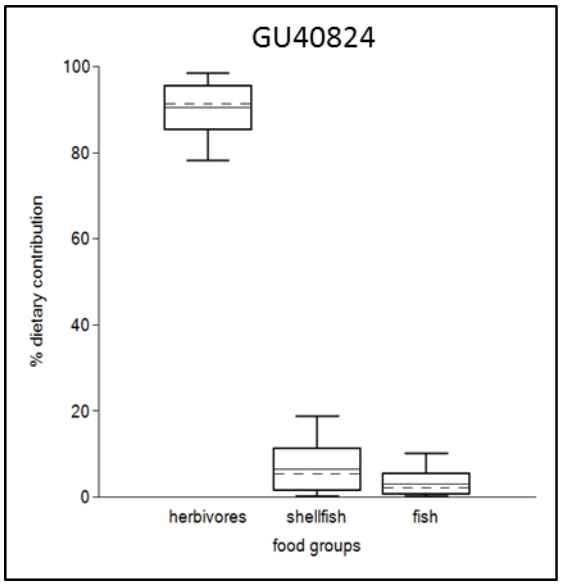
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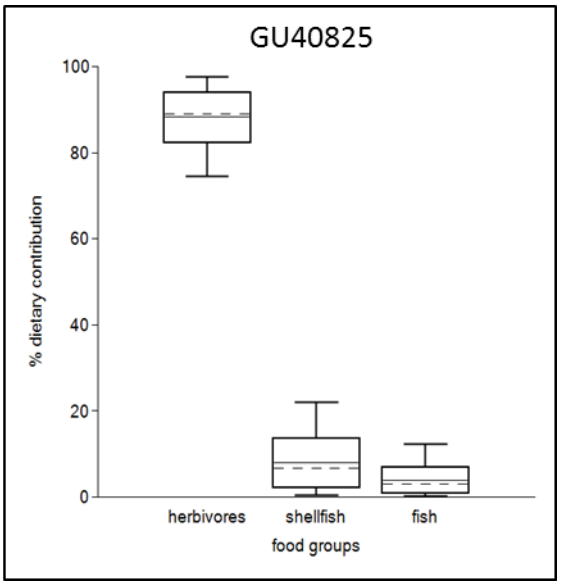
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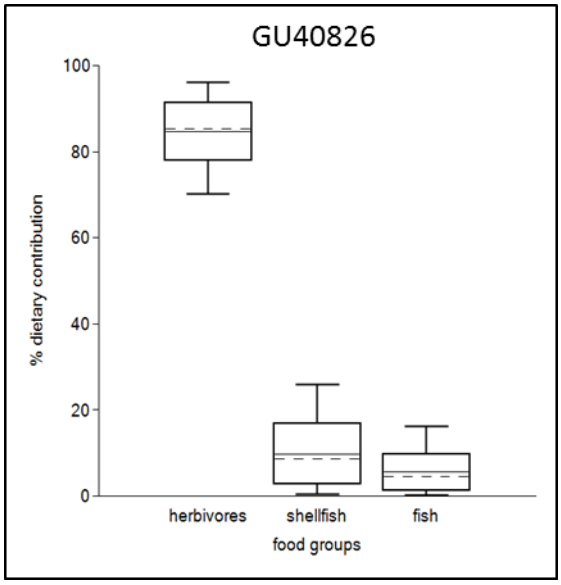
GU40826
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0
% dietary contribution
herbivores
shellfish
fish
food groups

Table 6.16 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for human bone collagen samples from Raschoille Cave.

Sample ID	Site name	Marine fish contribution (%±1σ)	Marine Shellfish contribution (%±1σ)	Terrestrial herbivore contribution (%±1σ)
GU40818	Raschoille cave	4±3	8±6	88±6
GU40819	Raschoille cave	3±3	6±5	91±5
GU40820	Raschoille cave	3±3	6±5	91±5
GU40821	Raschoille cave	4±4	9±6	87±6
GU40822	Raschoille cave	6±5	12±8	82±8
GU40823	Raschoille cave	6±5	11±8	83±7
GU40824	Raschoille cave	8±6	12±6	80±7
GU40825	Raschoille cave	9±6	12±8	79±8
GU40826	Raschoille cave	5±4	10±7	85±7

Raschoille Cave had the largest human sample population measured in this research. The results of the dietary reconstructions using FRUITS were comparable to many other Neolithic sites in this thesis. The dietary patterns seen here match those in Carding Mill Bay, Embo, the Holm of Papa Westray, Loch Borralie and the three tombs at Caithness. What is remarkable about this finding is that these sites are scattered across Scotland, from Orkney, to the north coast, the east coast and the west coast. This strongly suggests that, although there were slight variations between sites, the typical Neolithic diet included some fish and shellfish and that shellfish were the most important marine resource.

The use of shellfish as a food and bait at Raschoille Cave was evaluated by Pickard and Bonsall (2014). The contribution of different shellfish species to diet was assessed here and at three other sites (An Corran, Carding Mill Bay II and Ulva Cave). There was some variation in the range of species present on site, indicating some dietary diversity (Pickard and Bonsall, 2014). Both wild and domestic terrestrial herbivores were found alongside marine fish, shellfish and mammal remains. This variety in diet is reflected in the faunal bone assemblages as well as the shellfish remains in Scotland (Pickard and Bonsall, 2012). However, the two most abundant species on each site were limpets and periwinkles (72-98%

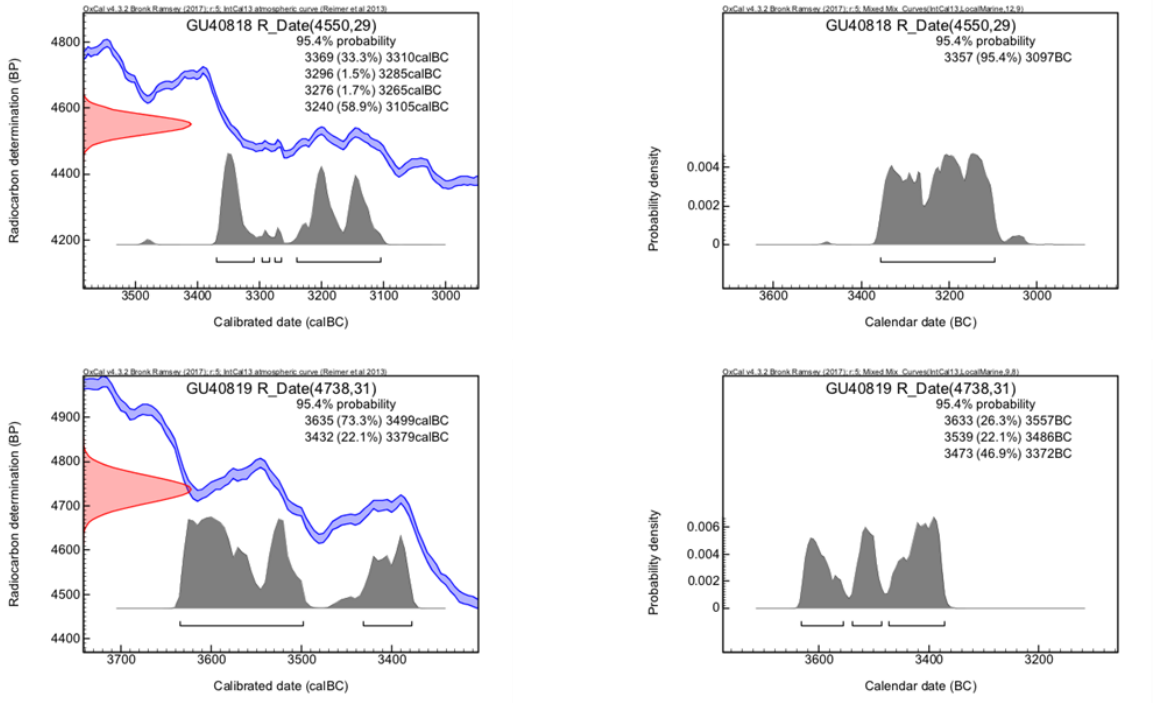
of the assemblages), so although there was variation in the species consumed, these two species represent the staple shellfish yield (Pickard and Bonsall, 2014). The findings here increasingly suggested that there was a dietary standard across the whole of Scotland, with small variations observed in some sites.

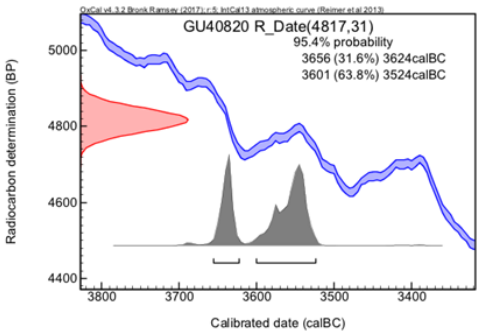
Shellfish foraging practices between 9500 to 3000 cal BC, as indicated by the shellfish assemblages, were also evaluated by Pickard and Bonsall (2014). The variety of species in each assemblage and the nature of each site suggested that shellfish were generally collected opportunistically from the most easily accessible part of the coastline – the intertidal zone. In the case of limpets, (the most abundant species present), Pickard and Bonsall linked their findings with past data to suggest that these shellfish were harvested at night while the animals were feeding. This argument was based on experimental harvesting of limpets which concluded that dislodging them forcefully with stone tools during the day, when the animals are stationary and securely attached to their 'home' rock, caused cracking damage to the shells (Russell et al., 1995). However, this finding was not replicated when using the same technique to collect over 100 individual limpet samples for the research presented in this thesis at various sites across Scotland.

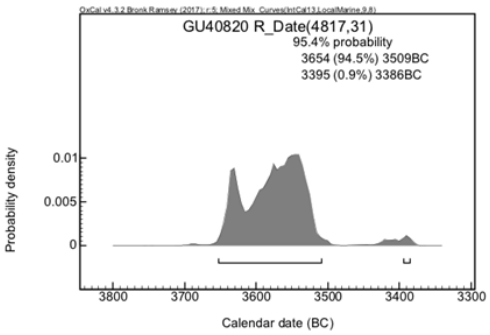
Table 6.17 Summary of recalibrated radiocarbon dates of humans from Raschoille Cave. Calibrated age ranges calculated using the terrestrial IntCal13 curve. Recalibrated ages calculated using the mixed marine-terrestrial curve, a ΔR value of -68 ± 90 ^{14}C yrs and dietary estimates derived using FRUITS. Reported with 95% confidence interval.

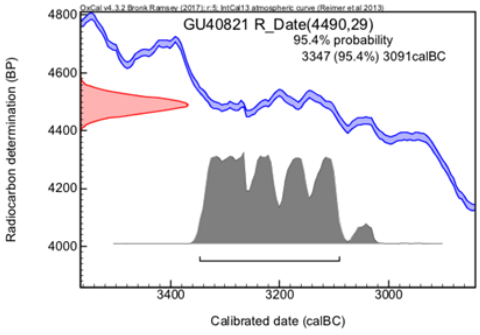
Sample ID	**Radiocarbon age (BP)**	**Calibrated age range (cal BC)**	**Recalibrated age range (cal BC)**
GU40818	4550±29	3369-3105	3357-3097
GU40819	4738±31	3635-3379	3633-3372
GU40820	4817±31	3656-3524	3654-3386
GU40821	4490±29	3347-3091	3341-2944
GU40822	4499±29	3346-3097	3337-2941
GU40823	4668±29	3619-3367	3627-3130
GU40824	4432±31	3328-2927	3310-2891
GU40825	4731±29	3625-3377	3630-3350
GU40826	4638±31	3517-3357	3516-3120

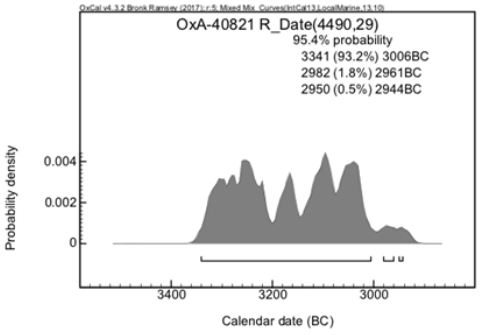
Figure 6.14 Recalibrated radiocarbon dates of humans from Raschoille Cave using a ΔR value of -68 ± 90 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Dates on the left have been calibrated using the terrestrial IntCal13 curve. Dates on the right have been calibrated using the mixed marine/terrestrial curve

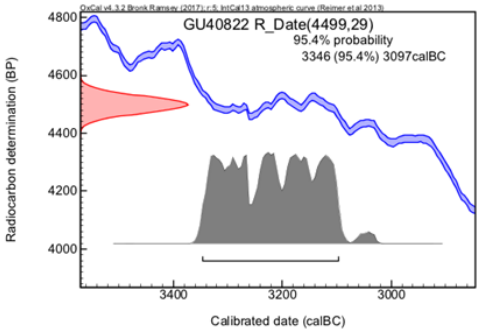


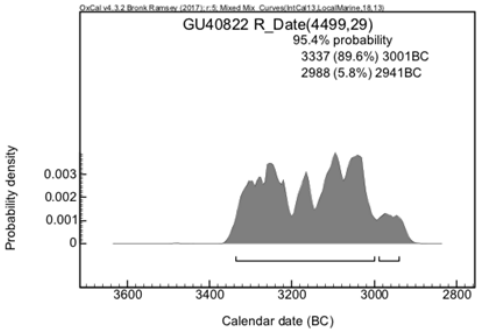

GU40820 R_Date(4817,31)
95.4% probability
3656 (31.6%) 3624calBC
3601 (63.8%) 3524calBC
Radiocarbon determination (BP)
Calibrated date (calBC)

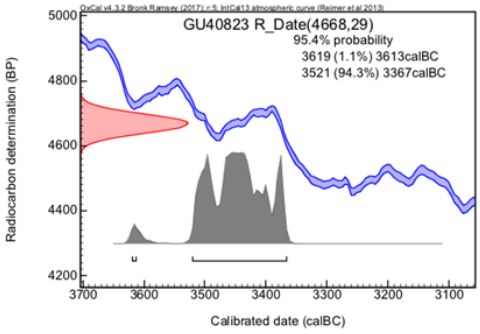

GU40820 R_Date(4817,31)
95.4% probability
3654 (94.5%) 3509BC
3395 (0.9%) 3386BC
Probability density
Calendar date (BC)

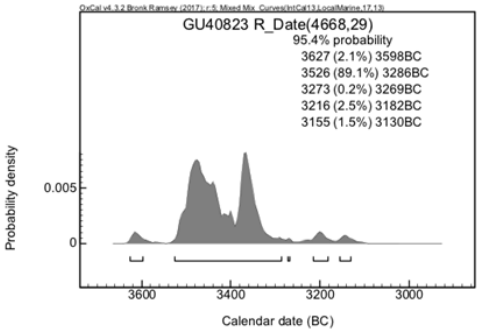

GU40821 R_Date(4490,29)
95.4% probability
3347 (95.4%) 3091calBC
Radiocarbon determination (BP)
Calibrated date (calBC)

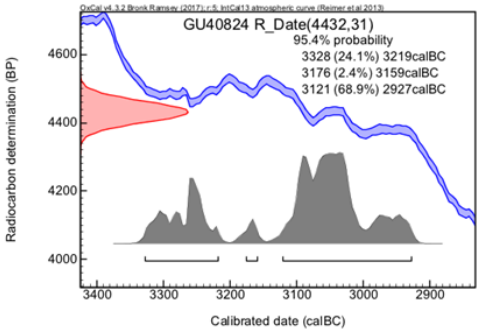

OxA-40821 R_Date(4490,29)
95.4% probability
3341 (93.2%) 3006BC
2982 (1.8%) 2961BC
2950 (0.5%) 2944BC
Probability density
Calendar date (BC)

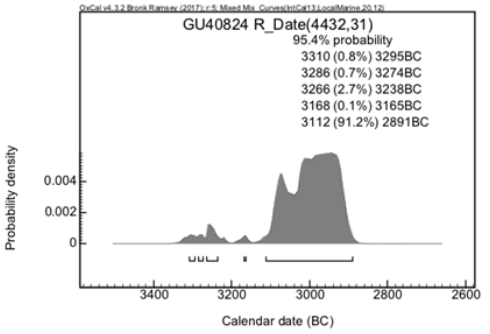

GU40822 R_Date(4499,29)
95.4% probability
3346 (95.4%) 3097calBC
Radiocarbon determination (BP)
Calibrated date (calBC)

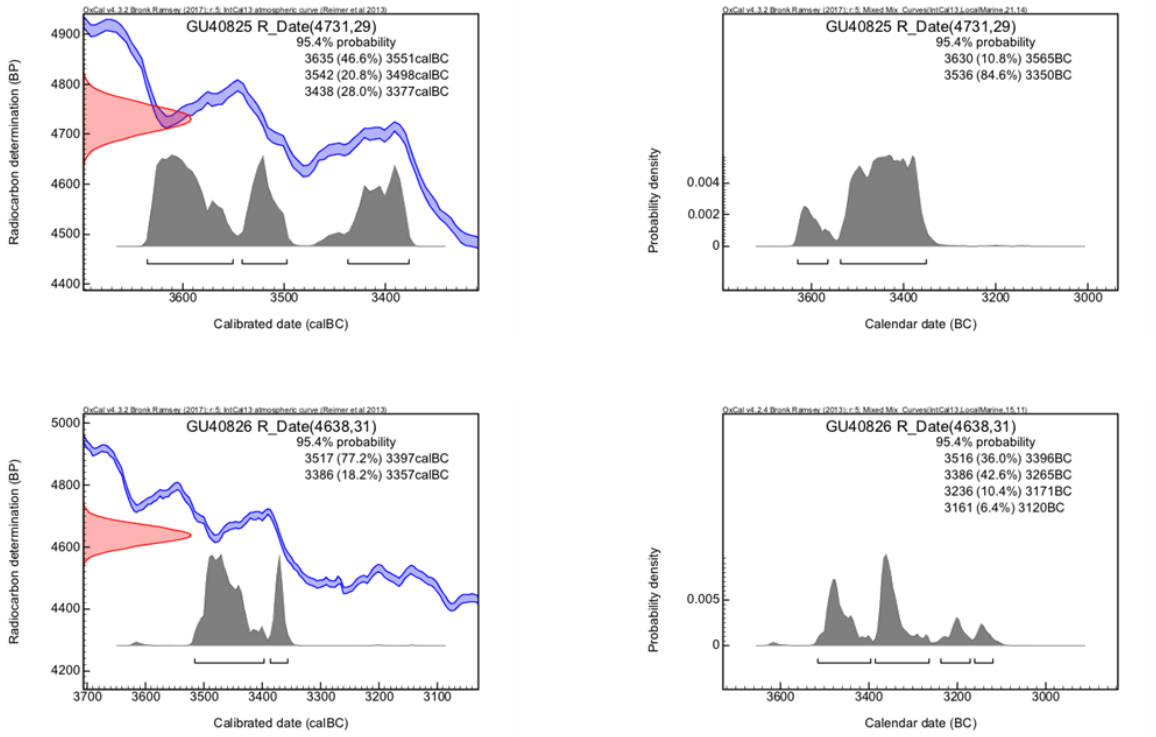

GU40822 R_Date(4499,29)
95.4% probability
3337 (89.6%) 3001BC
2988 (5.8%) 2941BC
Probability density
Calendar date (BC)


GU40823 R_Date(4668,29)
95.4% probability
3619 (1.1%) 3613calBC
3521 (94.3%) 3367calBC
Radiocarbon determination (BP)
Calibrated date (calBC)


GU40823 R_Date(4668,29)
95.4% probability
3627 (2.1%) 3598BC
3526 (89.1%) 3286BC
3273 (0.2%) 3269BC
3216 (2.5%) 3182BC
3155 (1.5%) 3130BC
Probability density
Calendar date (BC)


GU40824 R_Date(4432,31)
95.4% probability
3328 (24.1%) 3219calBC
3176 (2.4%) 3159calBC
3121 (68.9%) 2927calBC
Radiocarbon determination (BP)
Calibrated date (calBC)


GU40824 R_Date(4432,31)
95.4% probability
3310 (0.8%) 3295BC
3286 (0.7%) 3274BC
3266 (2.7%) 3238BC
3168 (0.1%) 3165BC
3112 (91.2%) 2891BC
Probability density
Calendar date (BC)



The radiocarbon dates for the nine human individuals at Raschoille cave, once recalibrated to take into account marine resource consumption for each individual, follow the same trend seen at all other Neolithic sites. In the cases of GU480823 and GU40826, the age ranges of the samples almost double in years (see Table 6.17 and Figure 6.14). All of the dates from Raschoille cave decreased in precision following re-evaluation, but because they are based on more reliable estimates of diet using the archaeological evidence, stable isotope analysis and Bayesian modelling (FRUITS), the new dates are arguably more accurate than previous calculations.

Holm of Papa Westray

Four human bone collagen samples were analysed from the Holm of Papa Westray and compared to the radiocarbon dates of three further individuals at the site from the literature (Schulting and Richards, 2009). The terrestrial baseline for individuals from the Holm of Papa Westray was comprised of previously published values detailed in Table 5.25 (Schulting and Richards, 2009), as well as new measurements taken from the nearby site of the Links of Noltland, Westray. The new faunal bone collagen isotope measurements were

considered a suitable isotopic baseline for the measurements on humans from the Holm of Papa Westray since Westray and Papa Westray were thought to have been connected by land in the Neolithic period (Ritchie et al., 1983). The faunal terrestrial samples measured for this research were cattle, sheep and red deer, reflecting the species that were present at the Holm of Papa Westray (Harman, 2009). A large midden comprising over 10,000 limpet shells was noted in the cairn, with other species such as razorfish, winkle, cockle and whelks also present (Maleszka-Ritchie, 2009). Sieving was employed during excavation and this resulted in the recovery of over 12,500 fish bones with cod, ling, saithe, haddock, pollock and wrasse identified in the collection (Harland and Parks, 2009). As these were the remains present on the site, the marine fish and shellfish baselines were comprised of all species measured in this thesis. Otter remains were also noted on the site, therefore, isotope values of otter were utilised from new and previously published measurements to represent the marine mammal food group (Schulting and Richards, 2009).

Table 6.18 Summary information for human bone collagen samples from the Holm of Papa Westray, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements.

Sample ID	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
GU41553	Bag 4, Sample 1	-20.9	9.9	3.3	4651±33
GU41554	Bag 4, Sample 2	-19.2	10.5	3.1	4697±33
GU41555	3 E 3, Sample 1	-18.4	10.8	3.3	4754±36
GU41556	3 E 3, Sample 2	-19.8	11.1	3.3	4525±36

Figure 6.15 FRUITS reconstructions of individuals from the Holm of Papa Westray. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

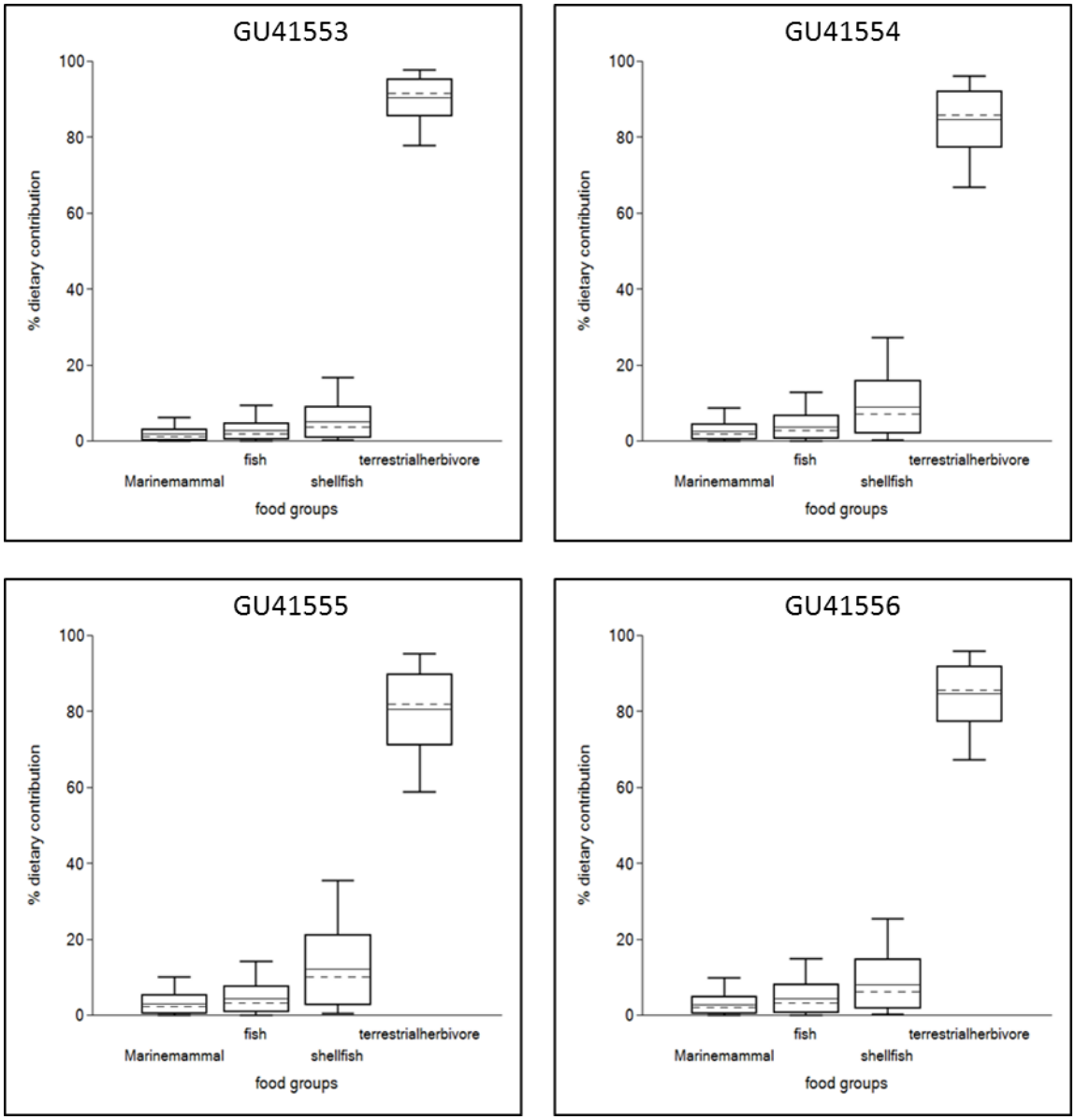


Table 6.19 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contributions to the human diet based on human bone collagen samples from Raschoille Cave.

Sample ID	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
GU41553	2±2	3±3	5±5	91±5
GU41554	3±2	4±3	9±7	85±8
GU41555	3±3	4±4	12±9	81±9
GU41556	3±3	4±4	8±7	85±7

The FRUITS data in Figure 6.15 and Table 6.19 show that the dietary habits at the Holm of Papa Westray correlate with the trends seen at Carding Mill Bay, Embo, Raschoille Cave and the three tombs at Caithness, but with minor variations. The dietary models show a largely terrestrial diet at the site, supplemented with some marine protein; however, there is evidence from previous research that sheep on the site ate seaweed Balasse and Tresset (2009), and this may also explain the marine contribution to the human samples.

After initial confusion was caused by anomalous $\delta^{13}C$ values of sheep bone collagen from the Holm of Papa Westray, an in-depth study was undertaken by Balasse and Tresset (2009). This work investigated whether the sheep were consuming seaweed through the analysis of $\delta^{13}C$ and $\delta^{18}O$ values of tooth enamel. The relatively elevated $\delta^{13}C$ values showed that the sheep were probably consuming marine protein via seaweed, and the oscillating $\delta^{18}O$ values suggested that this was occurring during the winter (Balasse and Tresset, 2009). Comparison of their results with samples from the Knap of Howar showed that, while sheep from Papa Westray displayed this 'foddering signal', sheep and cattle from Westray displayed evidence of a completely terrestrial diet (Balasse et al., 2006, Balasse and Tresset, 2007, Balasse and Tresset, 2009).

The findings in this research for the Holm of Papa Westray corroborate with previously published work. Schulting and Richards (2009) examined stable isotope values of humans and animals from the sites and concluded that there was "the possibility of a slight

contribution of marine protein" to the human diet (Schulting and Richards, 2009). Contrary to the conclusions here though, they suggested that the consumption of sheep may have caused the slight marine signal seen in the $\delta^{13}C$ values of human bone collagen. This is highly unlikely, since the seasonal consumption of seaweed in sheep produced only a slight marine effect in sheep bone collagen samples, and since sheep were not the only source of terrestrial protein available to the community at the Holm of Papa Westray, it does not follow that seaweed foddering in sheep could account for the amount of marine food groups seen in the FRUITS models for this site. It is far more likely, given the archaeological evidence on the site in the form of a variety of marine remains, that the humans were consuming fish, shellfish and marine mammals in addition to their mainly terrestrial diet.

There are both strengths and weaknesses in Schulting and Richards' (2009) interpretation of diet at the Holm of Papa Westray. In their study, stable carbon and nitrogen isotope measurements were undertaken on five bone collagen samples representing at least three individuals; three of these samples were subsequently radiocarbon dated. Analyses were carried out across two laboratories with some samples run at both to confirm inter-laboratory agreement. Careful consideration was also shown when selecting a faunal baseline for the human stable isotope measurements as contemporary samples from the Holm of Papa Westray and the nearby site of Knap of Howar were utilised. However, the representative nature of this sample size can be questioned, since it is not immediately apparent how many single samples make up the terrestrial baseline, and only a single otter bone represents the marine baseline. It was interpreted that diet of adults at the site were predominantly terrestrially sources, but that there could also be some marine input (Schulting and Richards, 2009).

As part of the 2009 study, linear interpolation was used to estimate the abundance of marine protein in the diet of three individuals. A site specific 100% marine endpoint was noted from the measurement of otter bone collagen, but subsequently discarded in favour of an average value for the Holocene Atlantic (Barrett et al., 2000). The justification for this was that, because there are natural variations in dietary endpoints, that taking the extreme values (i.e. the otter measurement at $\delta^{13}C$=-10.5‰) would be 'misleading' (Schulting and Richards, 2009). While this statement is somewhat justified, it could be argued that the use of a chronologically incomparable value is equally misleading. The resulting estimates of marine contribution to the diet for the three samples were c.16%, c.13% and c.2%. No uncertainty was attributed to these estimates, and the findings underestimate the importance of marine

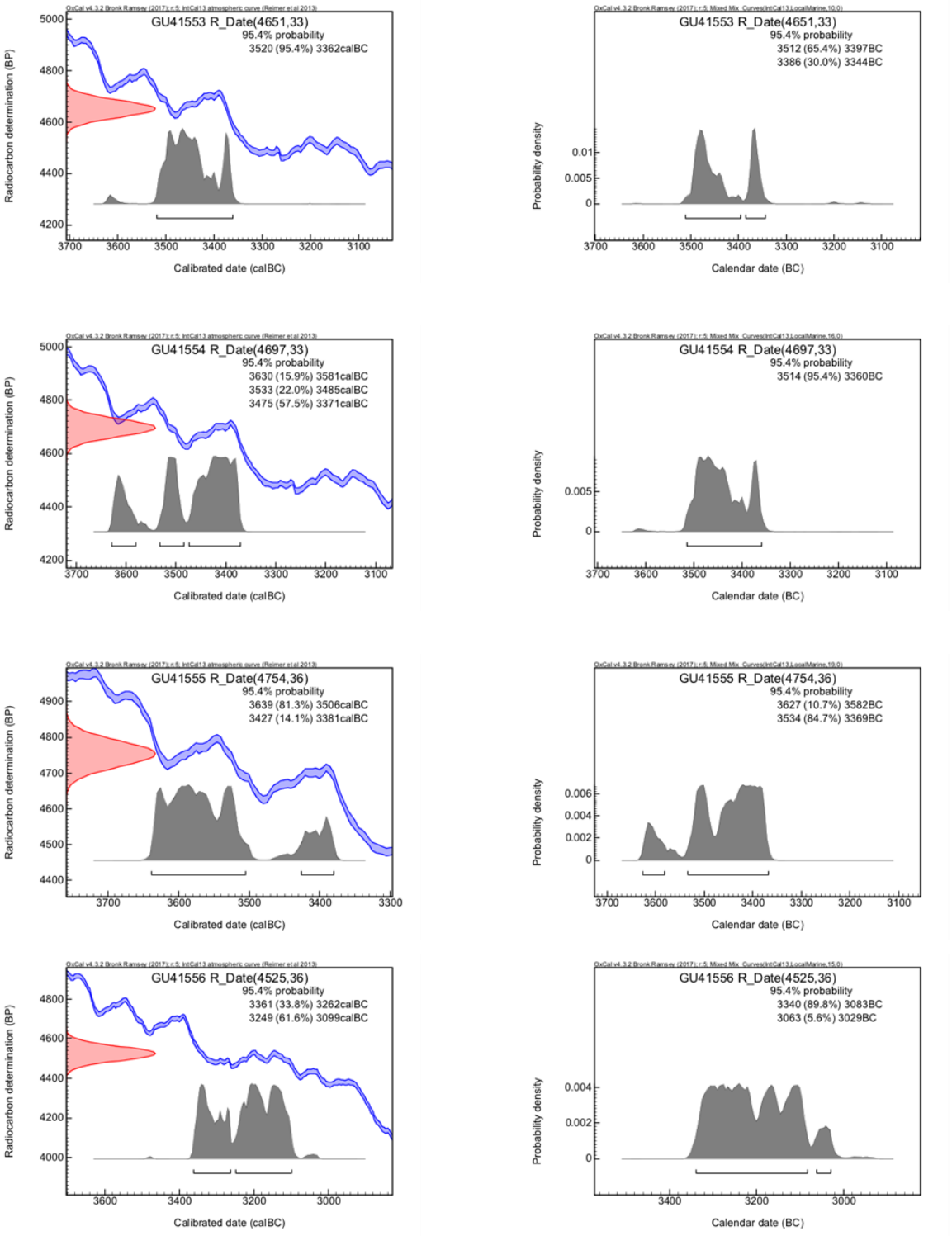
resources on the site in comparison to the archaeological evidence and the FRUITS models in this thesis. In addition, when discussing the results, they hedge their assumptions by downplaying importance of marine resources, stating that, the "overall contribution to the diet was small, if detectable with some effort" (Schulting and Richards, 2009). It was considered that the conclusions of this study would benefit from re-consideration using the method applied in this thesis.

When considering the dietary estimates of the four human individuals from the Holm of Papa Westray, using stable isotope analysis and FRUITS, marine foods are detected in abundances of up to 19±16%. This is very similar to the results seen from Embo, Carding Mill Bay, Raschoille Cave, and the tombs of Tuloch an t'Sionnach and Tulloch of Assery A and B with the exception that marine mammals were considered a food group at the Holm of Papa Westray, since otter remains were discovered during excavation. This is another example of the typical Neolithic diet seen during this research with small regional variations found in Scottish sites, as outlined in Bishop et al. (2009). The fact that FRUITS estimates that the smallest contributor of dietary marine protein comes from marine mammals and that otters were the least represented food group is also another example of the reconciliation of isotopic and archaeological evidence.

Table 6.20 Summary of recalibrated radiocarbon dates of humans from the Holm of Papa Westray. Calibrated age ranges calculated using the terrestrial IntCal13 curve. Recalibrated ages calculated using the mixed marine-terrestrial curve, a ΔR value of -47 ± 52 ^{14}C yrs and dietary estimates derived using FRUITS. Reported with 95% confidence interval. Samples prefixed with 'GU' are new measurements, samples prefixed with 'GrA' are measurements from Schulting and Richards (2009).

Sample ID	**Radiocarbon age (BP)**	**Calibrated age range (cal BC)**	**Recalibrated age range (cal BC)**
GU41553	4561±33	3520-3362	3512-3344
GU41554	4697±33	3630-3371	3514-3360
GU41555	4754±36	3639-3381	3627-3369
GU41556	4525±36	3353-3099	3340-3029
GrA25636	4715±40	N/A	3630-3330
GrA25638	4690±40	N/A	3630-3130
GrA25637	4640±40	N/A	3520-3120

Figure 6.16 Recalibrated radiocarbon dates of humans from the Holm of Papa Westray using a ΔR value of -47 ± 52 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Dates on the left have been calibrated using the terrestrial IntCal13 curve. Dates on the right have been calibrated using the mixed marine/terrestrial curve



When re-evaluating the radiocarbon data, there was no shift observed in the chronology of the humans at the Holm of Papa Westray. The radiocarbon dates showed less precision but arguably more accuracy when marine consumption, as indicated by FRUITS, is taken into account. Interestingly, these dates overlap with those produced by Schulting and Richards (see Table 6.20). This is also the dietary pattern for humans from the Neolithic sites of Embo and Carding Mill Bay, whereby a diet comprised of approximately 20% marine protein, does not alter the radiocarbon dates of the human remains. The emerging assumption regarding diet from the data analysed so far, is that, while we must reconsider the dietary habits of Scottish populations during the Neolithic, we can be confident about the previously established chronology of these sites.

Embo

The chambered cairn at Embo contained shell and animal remains, but the species of these are unknown (Bishop et al., 2009). There were no animal remains available to sample from Embo, so the dietary baseline was calculated from the average terrestrial herbivore baseline value for all sites in Scotland, and all shellfish and fish baseline measurements available. Like Cnoc Coig, caution should be exercised when interpreting the FRUITS output at this site since we do not have enough archaeological evidence to confidently inform the isotopic reconstruction and the terrestrial baseline is not site specific.

Table 6.21 Summary information for human bone collagen from Embo, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements. Context information was unavailable and is recorded as N/A.

Sample ID	Context	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C/N atomic ratio	Radiocarbon Age (^{14}C yrs BP±1σ)
GU40816	N/A	-21.6	11.0	3.3	4403±31

Figure 6.17 FRUITS reconstructions of individual GU40816. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

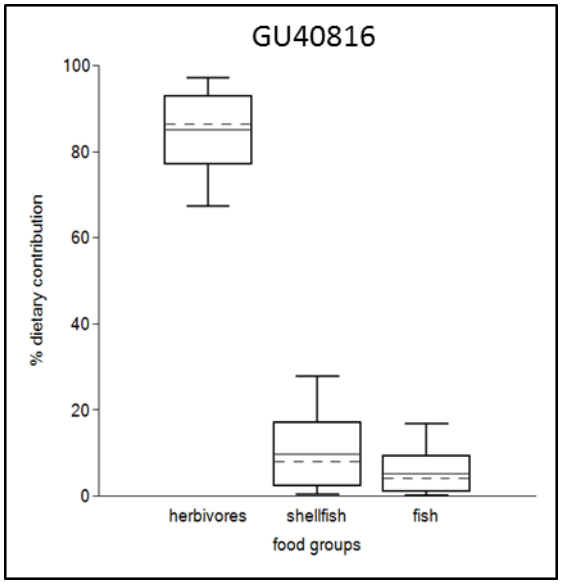


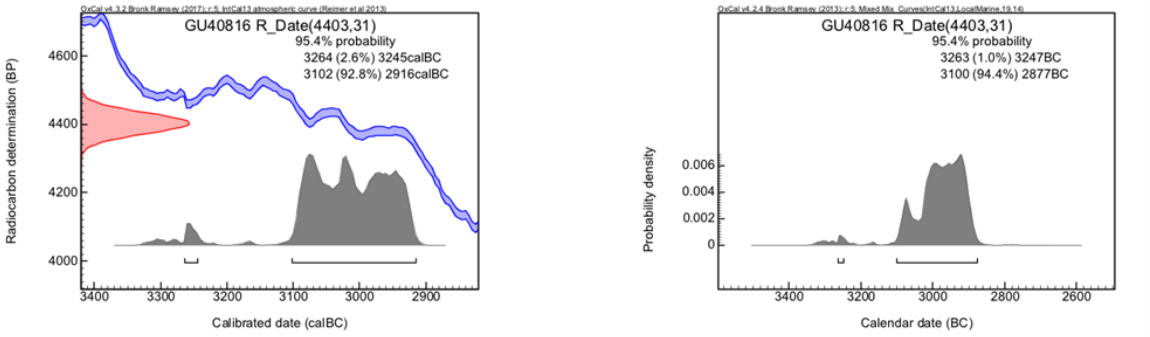
Table 6.22 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contributions to the human diet based on human bone collagen samples from Embo.

Sample ID	**Site name**	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
GU40816	Embo	N/A	8±6	11±8	81±8

The dietary reconstruction using FRUITS for the individual from Embo (Figure 6.17 and Table 6.22) revealed a diet comprised of mostly terrestrial resources (81% ± 8) and supplemented by fish (8% ± 6) and shellfish (11% ± 8). This dietary pattern mirrored that seen at the site of Carding Mill Bay and other Neolithic sites investigated as part of this research, where results indicated that shellfish are more important than fish in a predominantly terrestrial diet. This strengthens the argument that these models reflect a typical diet in the Neolithic that did not vary between the north and west coasts of Scotland.

This assertion can only be tentative at this point, given that the comparison of two sites cannot be considered representative of Scottish Neolithic diet. Indeed, Bishop et al. (2009) included Embo in their analysis of wild and domesticated plant consumption in the Neolithic and concluded that the subsistence economy was diverse: consisting of both cultured and gathered food. So, while the results presented here suggest that the typical Neolithic diet was comprised of mostly terrestrial resources and supplemented by marine foods, it is not to say that the types (species) of these resources did not vary between regions and communities.

Figure 6.17. Recalibrated radiocarbon dates of the human from Embo using a ΔR value of -47 ± 52 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS.



Though the FRUITS model indicated that the human from Embo sourced 19% ± 14 of their diet from the marine environment, this does not significantly affect the radiocarbon date of the bone collagen sample. The date calibrated using the terrestrial calibration curve is slightly less precise when using the more accurate chronological representation using mixed marine/terrestrial calibration curve, the estimation of marine carbon in the sample from FRUITS and the ΔR value for Scotland (-47 ± 52 ^{14}C yrs). The age was altered from 3264 to 2916 cal BC to 3263 to 2877 BC. This date placed Embo in the same chronological context as Carding Mill Bay, and it is interesting that humans from the two sites consumed a very similar diet, despite being located more than 150 miles away from each other. It can be argued that this points towards the typical Scottish Neolithic diet including a small amount of marine protein as standard.

Quoyness

Two human bone samples from Quoyness were available for stable isotope analysis and radiocarbon dating (see Table 6.23 for summary information). As at Loch Borralie, there was considerable uncertainty surrounding what food groups should be included in the dietary reconstructions for Quoyness. The faunal assemblages are only briefly mentioned in Childe (1952), so there was a lack of confidence regarding the species that were represented at the site. The baseline from Pool was utilised as the terrestrial baseline, and all available fish and shellfish species were included in the marine baseline. Caution must be demonstrated when evaluating the reliability of the FRUITS estimates at this site since there is a lack of archaeological evidence to support the isotopic data.

Table 6.23 Summary information for human bone collagen samples from Quoyness, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements. Context information was unavailable for both samples and is recorded as N/A in each case.

Sample ID	**Context**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ (‰)**	**C/N atomic ratio**	**Radiocarbon Age (^{14}C yrs BP±1σ)**
GU40817	N/A	-20.4	10.8	3.3	4567±31
GU41549	N/A	-20.1	12.4	3.3	4384±36

Figure 6.18 FRUITS reconstructions of three dietary scenarios for individuals from Quoyness. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean

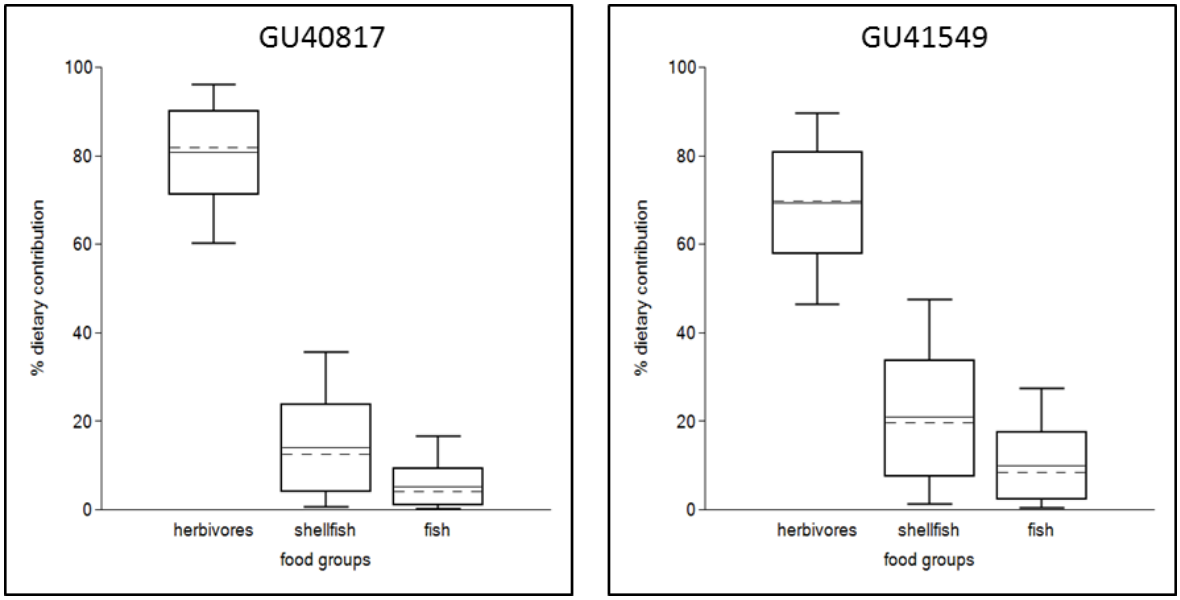


Table 6.24 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contributions to the human diet based on human bone collagen samples from Quoyness.

Sample ID	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
GU40817	N/A	5±4	14±9	81±9
GU41549	N/A	10±7	21±13	69±11

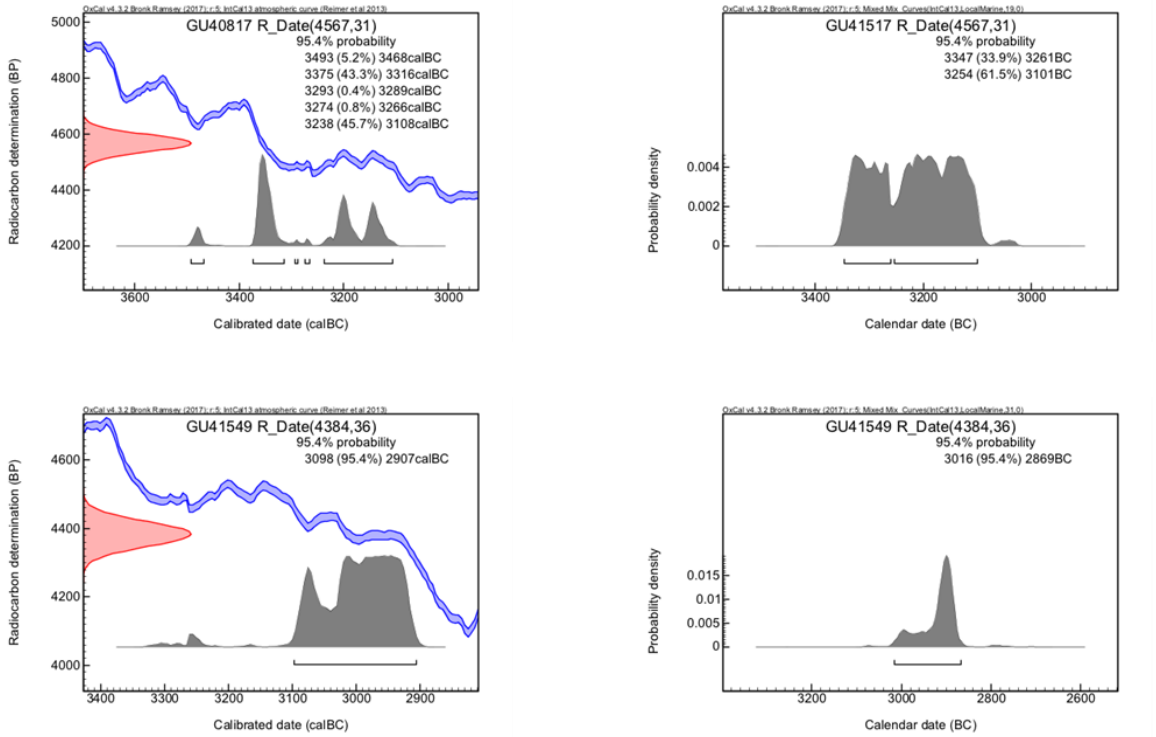
While one individual at Quoyness (GU40817) showed what is increasingly emerging as the typical Scottish Neolithic diet, the diet of the second individual (GU41549) appears distinct from all other comparable samples in this research. While all other samples analysed with FRUITS show a small amount of fish in the diet, this does not exceed 20% of the total dietary composition (see Table 6.24). While GU40817 also fits within this trend, with 81±9% of their diet coming from terrestrial sources, GU41549 is calculated as having sourced only

69±11% of their diet from the same source. This sample could represent an outlier in the Neolithic samples examined here; however, this particular result should be interpreted with caution for two reasons: firstly because of the previously discussed lack of detailed knowledge about the fauna present on the site, and secondly because of the large errors associated with the relative food group estimations. The abundance of shellfish consumed by GU41549 had an associated error of 13% and the estimation of terrestrial herbivore protein had an uncertainty of 11%. This is outside of the ideal margin of uncertainty for FRUITS estimates, as demonstrated by Fernandes et al. (2015). Therefore, although the dietary reconstructions for human bone samples from Quoyness are interesting, further work would be required on both human and faunal samples from this site in order to make any conclusive suggestions about the importance of marine resources here.

Table 6.25 Summary of recalibrated radiocarbon dates of humans from Quoyness. Calibrated age ranges calculated using the terrestrial IntCal13 curve. Recalibrated ages calculated using the mixed marine-terrestrial curve, a ΔR value of -47 ± 52 ^{14}C yrs and dietary estimates derived using FRUITS. Reported with 95% confidence interval

Sample ID	**Radiocarbon age (BP)**	**Calibrated age range (cal BC)**	**Recalibrated age range (cal BC)**
GU40817	4567±31	3493-3108	3347-3101
GU41549	4384±36	3098-2907	3016-2869

Figure 6.19 Recalibrated radiocarbon dates of humans from Quoyness using a ΔR value of -47 ± 52 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Date ranges on the left have been calibrated using the terrestrial IntCal13 curve. Date ranges on the right have been calibrated using the mixed marine/terrestrial curve



In addition to the differing diets detected in the two humans from Quoyness, there is also a chronological difference shown by radiocarbon results. The two radiocarbon ages differ by c.180 years (GU40817 4567±33 BP and GU41549 4384±36 BP). It is therefore possible that these two individuals were not part of the same community. When examining the dates calibrated with the IntCal13 calibration curve, statistical uncertainty narrows this chronological gap, though there is still no overlap (see Table 6.25 and Figure 6.19). When calibrated using the mixed marine/terrestrial curve and the FRUITS data, GU41549 is influenced by the MRE and is potentially c.85 years younger than originally calculated, broadening the chronological gap between these two samples. Again, caution must be exercised when considering the FRUITS estimates from these sites though, and it would be prudent to consider the date calibrated using the terrestrial calibration curve as more accurate unless reliability regarding the FRUITS dietary reconstructions here can be established.

Whatever way the radiocarbon measurements for the humans at Quoyness are approached, there is an interesting chronological distinction that is not seen in any other site in this research. If these individuals did indeed live at different times, it would make a reasonable

explanation as to why the dietary habits of these two humans are also different. One individual may well have lived in a community that existed generations after the other, and the diet and subsistence practices (e.g. the use of foddering animals or manuring crops) may have changed over that time period, resulting in differing bone collagen isotope 'signatures'.

Carding Mill Bay

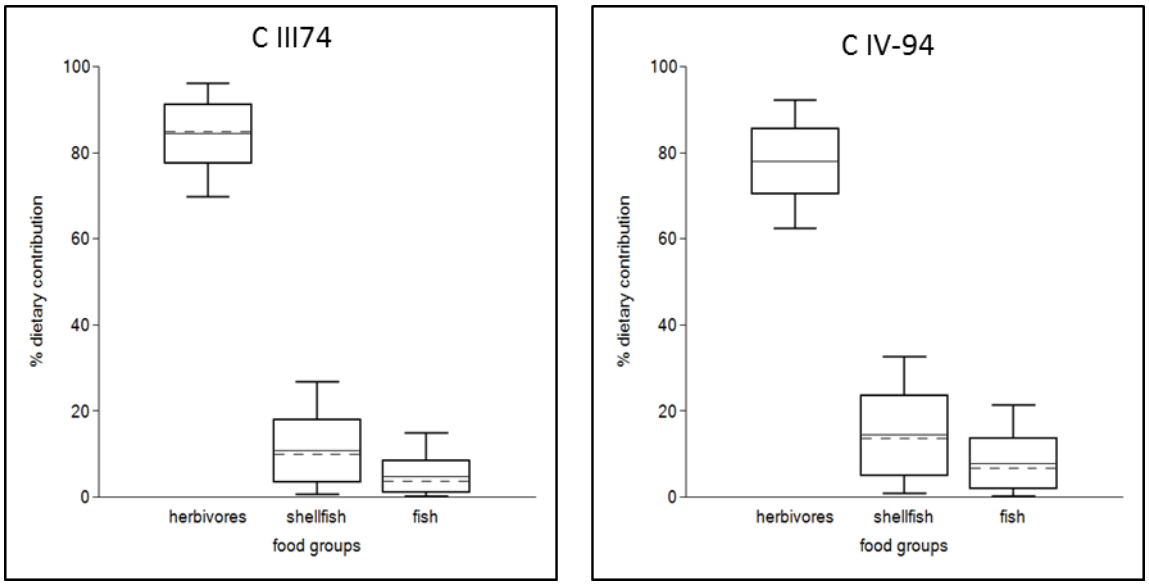
All ten of the human individuals from Carding Mill Bay that were investigated in this thesis had been analysed in a previous publication and are re-evaluated here (Schulting and Richards, 2002). Summary stable isotope and radiocarbon data are presented in Table 6.26. The faunal dietary baseline for the humans at Carding Mill Bay was assigned as follows: the terrestrial baseline was formed of examples of all terrestrial species available from the site. Eel, cod, poor cod, pollock, whiting and Gadidae (sp. Unidentifiable) were identified from the site, so all fish species that were measured were included in the marine fish baseline. Eighteen species of shellfish were recovered from the site, with the predominant species being limpet and therefore all shellfish species measured in this research were assigned as the shellfish baseline. The dietary estimates of four human samples from Carding Mill Bay (OxA-7663, OxA-7664, OxA7665 and OxA-7890), and the findings from the stable isotope measurement of six further individuals published in Schulting and Richards (2002) correlate with the earlier dietary interpretations and serves to strengthen the argument presented below.

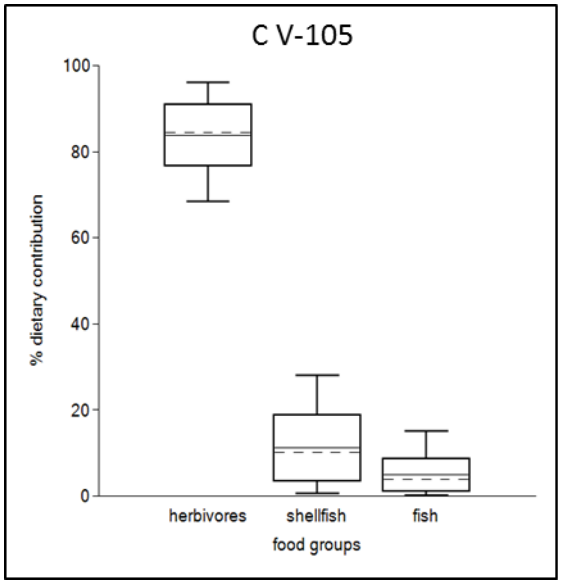
Table 6.26 Summary information for human bone collagen samples from Carding Mill Bay, including $\delta^{13}C$ and $\delta^{15}N$ values and radiocarbon measurements. N/A = no radiocarbon measurement exists for this sample.

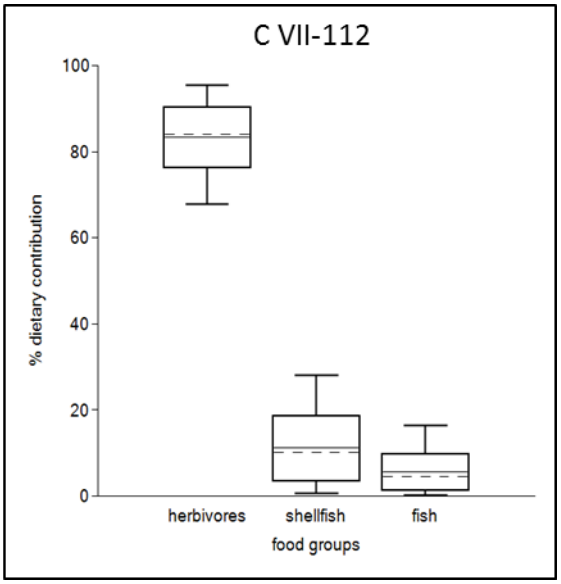
Sample ID	Site name	Context	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C/N atomic ratio	Radiocarbon Age (^{14}C yrs BP±1σ)
OxA-7663	Carding Mill Bay	C XIV:1	-21.5	9.0	3.2	4800±50
OxA-7664	Carding Mill Bay	C XV:1	-21.0	8.9	3.1	4830±45
OxA-7665	Carding Mill Bay	C VII:130	-21.5	9.6	3.2	4690±40

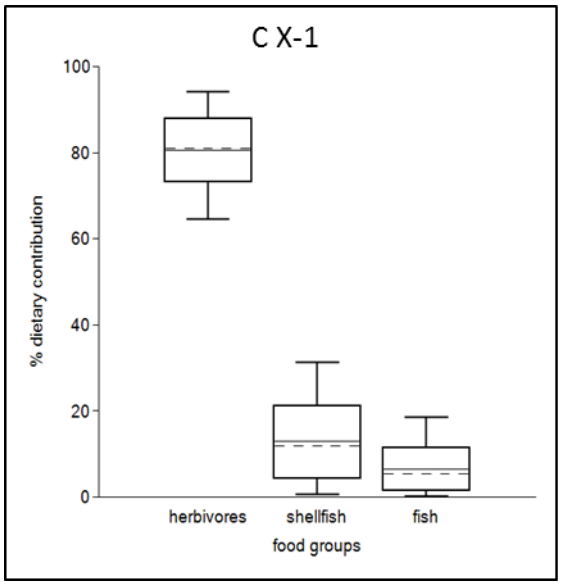
Sample ID	Site name	Context	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C/N atomic ratio	Radiocarbon Age (^{14}C yrs BP±1σ)
OxA-7890	Carding Mill Bay	C XXIII	-21.4	9.8	3.1	4330±60
C III:74	Carding Mill Bay	C III:74	-21.3	8.8	3.2	N/A
C IV:94	Carding Mill Bay	C IV:94	-21.5	10.0	3.1	N/A
C V:105	Carding Mill Bay	C V:105	-21.3	8.9	3.2	N/A
C VII:112	Carding Mill Bay	C VII:112	-21.3	9.1	3.2	N/A
C X:1	Carding Mill Bay	C X:1	-21.3	9.5	3.1	N/A
C XVII:1	Carding Mill Bay	C XVII:1	-21.9	9.9	3.1	N/A

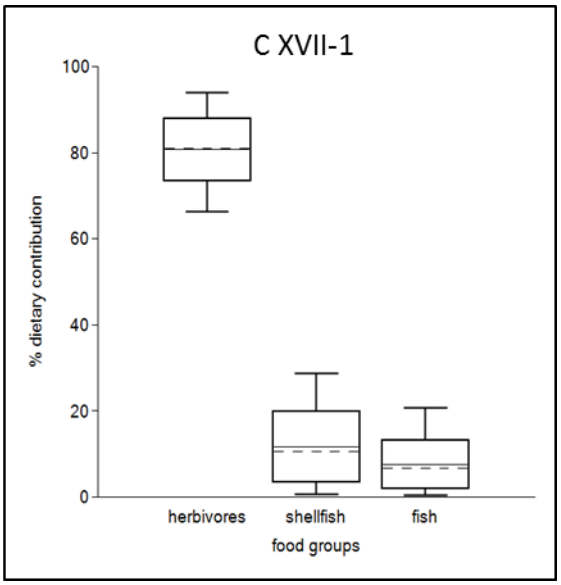
Figure 6.20 FRUITS reconstruction of individuals from Carding Mill Bay. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean. Stable isotope values for all samples were measured by Schulting and Richards (2002)




C V-105
% dietary contribution
100
80
60
40
20
0
herbivores
shellfish
fish
food groups


C VII-112
% dietary contribution
100
80
60
40
20
0
herbivores
shellfish
fish
food groups


C X-1
% dietary contribution
100
80
60
40
20
0
herbivores
shellfish
fish
food groups


C XVII-1
% dietary contribution
100
80
60
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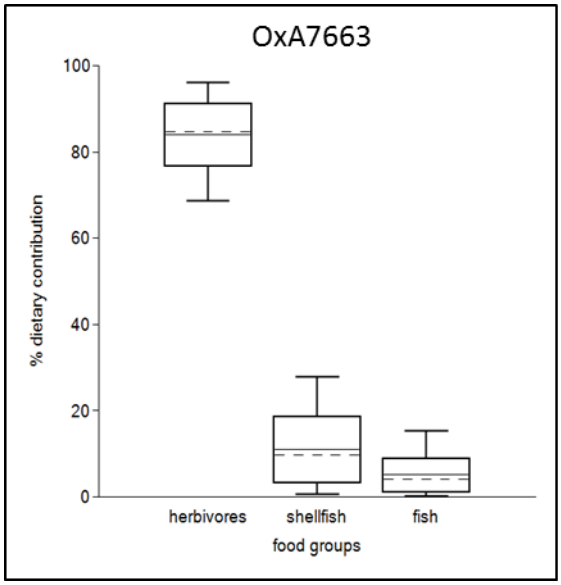
20
0
herbivores
shellfish
fish
food groups


OxA7663
% dietary contribution
100
80
60
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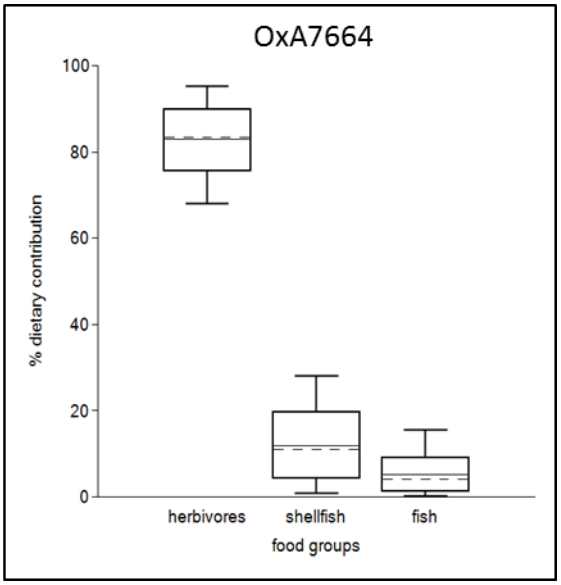
0
herbivores
shellfish
fish
food groups


OxA7664
% dietary contribution
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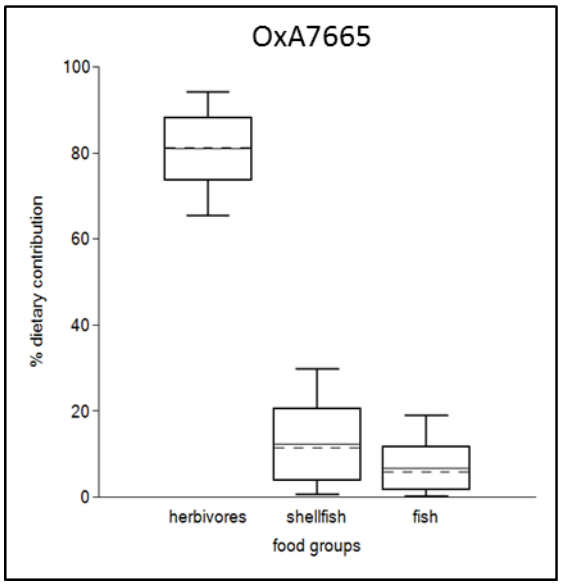
herbivores
shellfish
fish
food groups



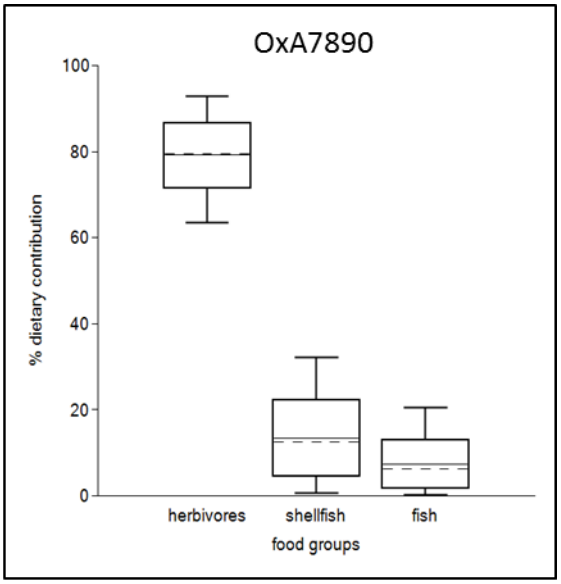


Table 6.27 FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contributions to the diet of humans from Carding Mill Bay.

Sample ID	**Site name**	**Marine mammals contribution (%±1σ)**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
OxA7663	Carding Mill Bay	N/A	5±4	11±7	84±7
OxA7664	Carding Mill Bay	N/A	5±4	12±7	83±7
OxA7665	Carding Mill Bay	N/A	7±5	12±8	81±7
OxA7890	Carding Mill Bay	N/A	7±6	13±9	79±8
C III:74	Carding Mill Bay	N/A	5±4	11±7	84±7
C IV:94	Carding Mill Bay	N/A	8±6	14±9	78±8
C V:105	Carding Mill Bay	N/A	5±4	11±7	84±7

C VII:112	Carding Mill Bay	N/A	6±4	11±7	83±7
C X:1	Carding Mill Bay	N/A	7±5	13±8	81±8
C XVII:1	Carding Mill Bay	N/A	8±6	12±8	81±7

In all human samples analysed from Carding Mill Bay, a diet comprised of mostly terrestrial resources, but supplemented with marine fish and shellfish was observed. The models suggested that shellfish were a more important resource at Carding Mill Bay than marine fish, and this was reflected in the archaeological record, with shellfish being far more abundant than fish remains (Connock et al., 1991). It seems likely that the use of marine resources at this time would have been secondary to farm produce, either as a supplement to the diet or as a famine food in times of crop/livestock failure. The findings at Carding Mill Bay have parallels with results derived from high resolution measurements of stable isotopes in tooth dentine from Neolithic individuals in Shetland (Montgomery et al., 2013). These showed that at least during their childhood years the people periodically and temporarily returned to eating marine resources before reverting back to a more terrestrial-based diet. The authors hypothesised that this was in response to difficulties encountered while attempting to maintain a sedentary farming culture in a marginal environment (Montgomery et al, 2013). While the bulk bone collagen isotope values in this research cannot reveal periodic returns to marine resources at different stages in life, they do show small inputs of marine resources to the diet, which is also evident in the results from Shetland.

Carding Mill Bay was chosen for an in-depth review as part of the study in Bownes et al (2017) since the MRE value at the site has been questioned in two previous studies, further clarity was sought (Ascough et al., 2004, Russell et al., 2015). New ΔR values were calculated for contexts XIV and XV at the site (see Table 6.28). For context XIV marine samples, one sample (GU39634) was excluded as an outlier and the remaining three samples passed the χ^2 test. However, the terrestrial samples failed the χ^2 test, with no two samples passing. On that basis, it was determined that context XIV is mixed and unsuitable for deriving a ΔR value. For context XV, one marine and one terrestrial sample (GU39638 and GU39631, respectively) were removed and the remaining three samples in both groups

passed the χ^2 test. In this case, context XV was deemed suitable for ΔR calculation. The calculated value was -130 ± 34 ^{14}C yrs (Bownes, et al, 2017).

Table 6.28 Range of ΔR values at Carding Mill Bay

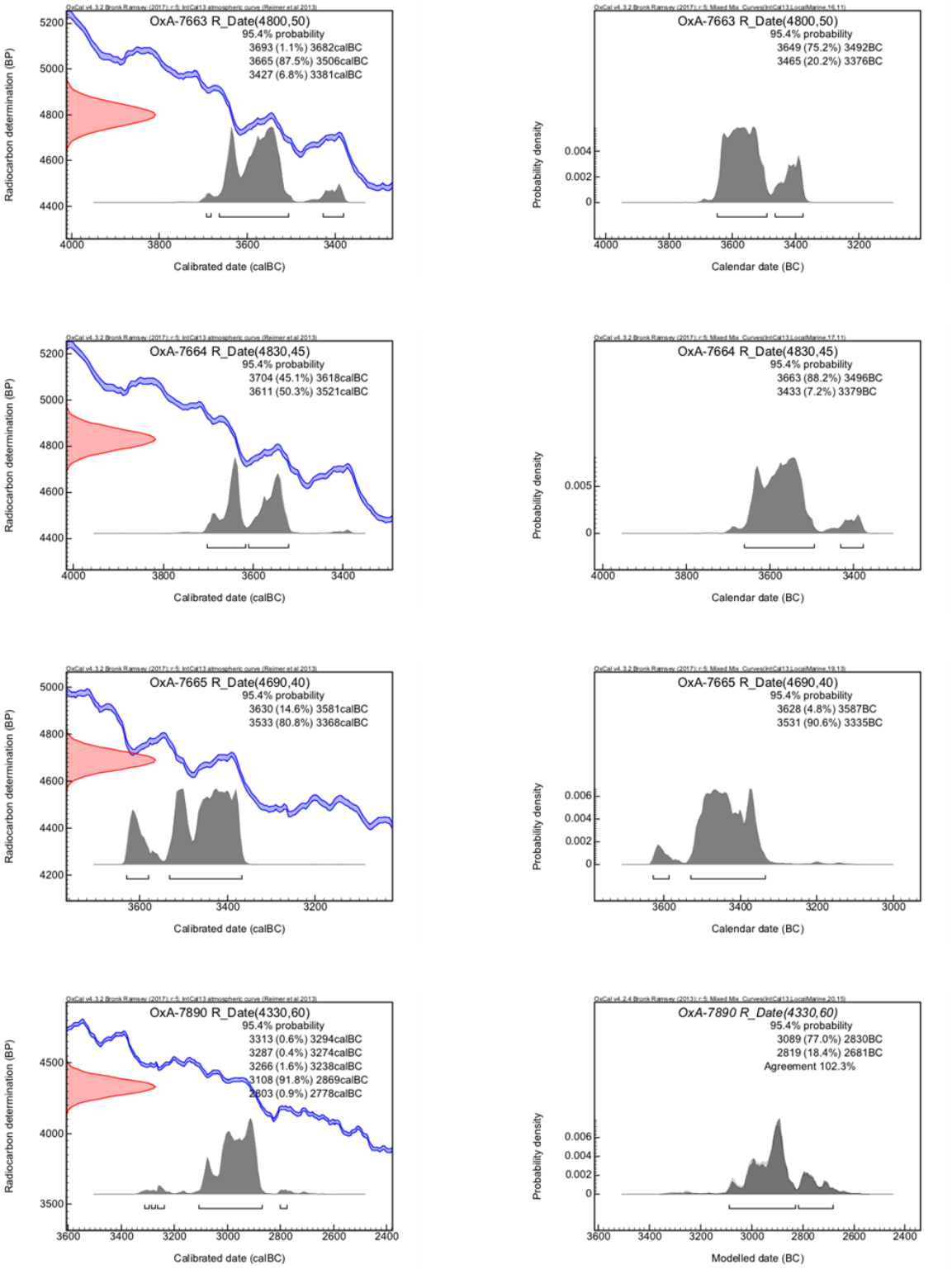
Context #	ΔR Value	Source
XIII	+150 ± 28	Ascough et al. (2007)
XIV	-44 ± 91	Reimer, et al, (2002)
XIV	-130 ± 34	This research
XV	+86 ± 67	Reimer, et al, (2002)

The radiocarbon ages for the four humans previously dated at Carding Mill Bay were first calibrated using the terrestrial calibration curve within OxCal 4.2, to provide baseline ^{14}C dates (Reimer et al., 2013). The ages were then re-calibrated using the mixed marine/terrestrial calibration curve within OxCal 4.2 (Reimer et al., 2002), employing the marine dietary information for each individual obtained from FRUITS, together with the recalculated ΔR value.

Table 6.29 Summary of recalibrated radiocarbon dates of humans from Carding Mill Bay. Calibrated age ranges calculated using the terrestrial IntCal13 curve by Schulting and Richards (2002). Recalibrated ages calculated using the mixed marine-terrestrial curve and dietary estimation derived using FRUITS. Reported with 95% confidence interval.

Sample ID	Radiocarbon age (BP)	Calibrated age range (cal BC)	Recalibrated age range (cal BC)
OxA-7663	4800 ±50	3693-3381	3649-3376
OxA-7664	4830 ±45	3704-3521	3663-3379
OxA-7665	4690 ±40	3630-3368	3628-3335
OxA-7890	4330 ±60	3313-2778	3095-2675

Figure 6.21 Recalibrated radiocarbon dates of humans from Carding Mill Bay using an updated ΔR value of -130 ± 34 ^{14}C yrs and percentage marine contribution to diet calculated using FRUITS. Dates on the left have been calibrated using the terrestrial IntCal13 curve. Dates on the right have been calibrated using the mixed marine/terrestrial curve



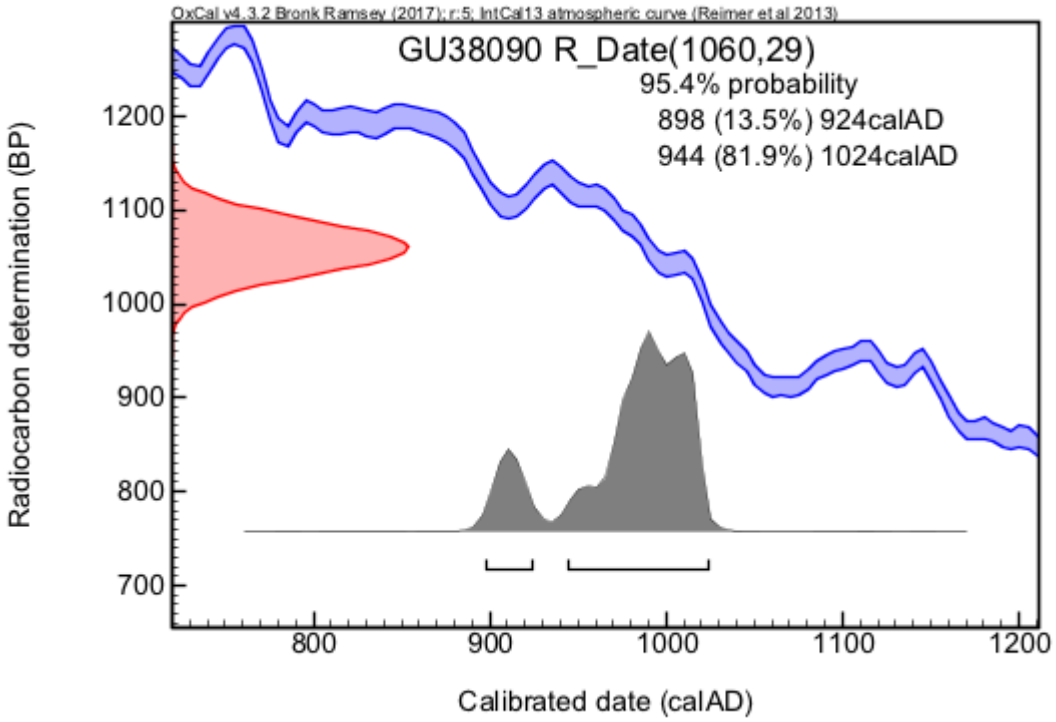
Following the recalibration of the four radiocarbon ages derived from human bone collagen, to take into account the improved ΔR value for the site and the potential marine reservoir effect caused by the consumption of shellfish and fish, there was very little shift in the ages. While Table 6.28 and Figure 6.21 show that the recalibrated ages are less precise than those calibrated using the terrestrial calibration curve, the updated ages are arguably more accurate. This is noteworthy, since, even after correction of the ages, these individuals date to the first half of the Scottish Neolithic; not only is the chronology of the site reliable and secure, but we show that fish and shellfish in the ancient diet can be associated with the Neolithic.

Crow Taing – An outlier site

The human bone collagen sample from Crow Taing was taken from the discrete burial of a child which was uncovered following a storm. The terrestrial fauna present at Crow Taing included cattle, sheep, red deer and pig, but were unavailable for sampling, so the isotope baseline from nearby Pool, Sanday was utilised. The marine fish isotope baseline was made up of all species measured since there was fish bone present on the site which were not identified to species. The most abundant shellfish on the site were limpets, but other non-specified shellfish were also present, so all species were included in the shellfish baseline. Seal and a whale bone were also noted at Crow Taing, so a fourth food group, 'marine mammals', was included in the dietary baseline and comprised of measurements from a sperm whale from Kirkwall and seal bone collagen sourced from modern individuals at Sanday.

In this case, it is pertinent to examine the date of the sample before the dietary reconstruction since the ^{14}C results were not as expected. The remains were a single discrete burial with no accompanying finds to place the child within a chronological context. Upon receiving the sample at SUERC, it was thought that the remains were probably Neolithic due to the rich evidence from the same period present at Crow Taing. As with all samples (except for those at Cnoc Coig) the radiocarbon date was first calculated using the Intcal13 calibration curve as this is how the sample would have been treated without any further insight from FRUITS. Figure 6.22 shows that the child at Crow Taing dated to 898-1024 cal AD and was actually a Viking period individual.

Figure 6.22 Calibrated radiocarbon dates of the human child from Crow Taing using the IntCal13 calibration curve



This presented problems when producing the FRUITS model for this sample as the nearest Neolithic site (Pool) was used to define baseline isotope values and food group assumptions. The confidence in the food group information was initially good as it was believed to be local and contemporary to the human remains. However, the Viking human remains are c.4000 years younger than the terrestrial samples used to produce the isotope baseline. The assumptions made about food groups in the diet were also based on fauna present at Neolithic Crow Taing, so cannot be confidently argued to reflect the correct food groups that the Viking age individual consumed. Since the radiocarbon date of this individual placed the sample outside of the chronological scope of this research, the dietary results were not included when all the findings in relation to the Mesolithic-Neolithic transition in Scotland were considered.

6.4.3 Summary of Findings from Human Stable Isotope and Radiocarbon Data and Implications for the Scottish Mesolithic-Neolithic Transition

Following the consideration of diet and chronology of the human remains at each site studied in this thesis, there are notable similarities that can be observed in the diet of Neolithic people in Scotland and the radiocarbon dates of their remains. A summary of dietary information for each human sample can be found in Table 6.29. Firstly, the FRUITS reconstructions of the vast majority of samples were found to be more precise than would be possible using linear interpolation, the most common method of characterising marine resources in past diet. Where the uncertainty associated with an estimation of a food group's contribution to diet is less than 10%, this is an improvement on the precision of the linear interpolation method. As has been discussed in many of the case studies, the fact that FRUITS is able to distinguish between marine mammals, marine fish and marine shellfish is also remarkable.

Table 6.30 Summary FRUITS estimates of marine mammal, marine fish, marine shellfish and terrestrial herbivore protein contribution to the diet for humans at all archaeological sites.

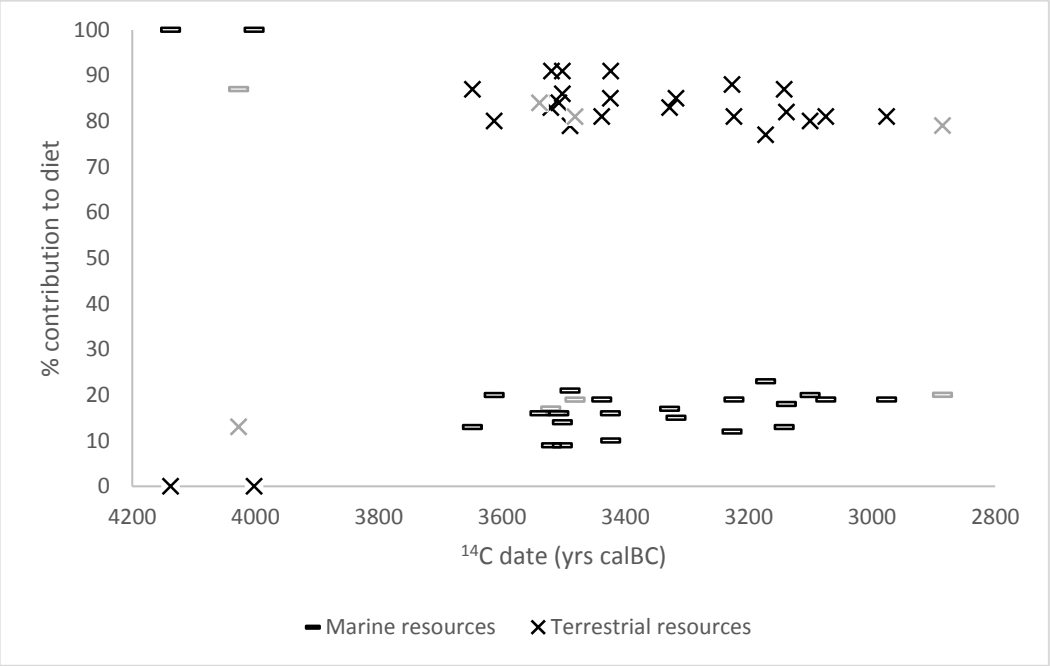
Sample ID	**Site name**	**Marine fish contribution (%±1σ)**	**Marine Shellfish contribution (%±1σ)**	**Terrestrial herbivore contribution (%±1σ)**
OxA-7663	Carding Mill Bay	5±4	11±7	84±7
OxA-7664	Carding Mill Bay	5±4	12±7	83±7
OxA-7665	Carding Mill Bay	7±5	12±8	81±7
OxA-7890	Carding Mill Bay	7±6	13±9	79±8
C III:74	Carding Mill Bay	5±4	11±7	84±7
C IV:94	Carding Mill Bay	8±6	14±9	78±8
C V:105	Carding Mill Bay	5±4	11±7	84±7
C VII:112	Carding Mill Bay	6±4	11±7	83±7
C X:1	Carding Mill Bay	7±5	13±8	81±8
C XVII:1	Carding Mill Bay	8±6	12±8	81±7
OxA-8005	Caisteal Nan Gillean II	42±26	43±24	15±10

Sample ID	Site name	Marine fish contribution (%±1σ)	Marine Shellfish contribution (%±1σ)	Terrestrial herbivore contribution (%±1σ)
OxA-8005 simplified	Caisteal Nan Gillean II	87±10	N/A	13±10
GU41836	Cnoc Coig	23±17	56±13	N/A
GU40827	Cnoc Coig	21±15	63±13	N/A
18104	Cnoc Coig	11±9	82±9	N/A
17157	Cnoc Coig	18±14	67±12	N/A
17203	Cnoc Coig	10±9	82±9	N/A
18284	Cnoc Coig	22±17	52±13	N/A
18089	Cnoc Coig	16±12	74±11	N/A
GUsi3943	Crow Taing	5±4	9±7	83±8
GU40816	Embo	8±6	11±8	81±8
GU41553	Holm of Papa Westray	3±3	5±5	91±5
GU41554	Holm of Papa Westray	4±3	9±7	85±8
GU41555	Holm of Papa Westray	4±4	12±9	81±9
GU41556	Holm of Papa Westray	4±4	8±7	85±7
GU36228	Loch Borralie	4±3	10±7	86±7
GU36229	Loch Borralie	5±4	15±9	80±9
GU40817	Quoyness	5±4	14±9	81±9
GU41549	Quoyness	10±7	21±13	69±11
GU40818	Raschoille cave	4±3	8±6	88±6
GU40819	Raschoille cave	3±3	6±5	91±5
GU40820	Raschoille cave	3±3	6±5	91±5
GU40821	Raschoille cave	4±4	9±6	87±6
GU40822	Raschoille cave	6±5	12±8	82±8
GU40823	Raschoille cave	6±5	11±8	83±7
GU40824	Raschoille cave	8±6	12±6	80±7
GU40825	Raschoille cave	9±6	12±8	79±8
GU40826	Raschoille cave	5±4	10±7	85±7
GU41551	Tulach an t'Sionnach	5±4	11±8	84±8

Sample ID	Site name	Marine fish contribution (%±1σ)	Marine Shellfish contribution (%±1σ)	Terrestrial herbivore contribution (%±1σ)
GU41552	Tulloch of Assery A	5±4	11±8	84±8
GU41550	Tulloch of Assery B	4±4	9±6	87±7

All humans, except for those from Cnoc Coig and Crow Taing were from Neolithic sites. What is remarkable about the data presented in Table 6.29 is that it was possible to differentiate between three different sub-groups of marine resources: marine mammals, marine fish and marine shellfish. In each Neolithic case, shellfish are more important than fish as a dietary resource. This finding was discussed in Bownes, et al (2017) with specific reference to the Carding Mill Bay samples; however, the conclusions can be applied to individuals from all Neolithic sites. Namely, the fundamental conclusion that can be drawn from FRUITS data is that shellfish were consumed in the Neolithic. Despite the assertion by some that marine foods were unimportant to the Neolithic lifestyle (e.g. Schulting and Richards, 2002, Richards and Schulting 2006), the abundance of shells at Neolithic sites and the results presented in this thesis strongly suggest that they were an important commodity. Shellfish were easily accessible and therefore represent a logical choice to Neolithic communities to supplement their largely terrestrial diet.

Figure 6.23 Summary of all estimates of marine and terrestrial resources in human diet reported in this thesis, plotted according to their recalibrated radiocarbon measurements. All dietary estimates are derived from FRUITS and are reported to the nearest 1%. All radiocarbon dates have been calibrated to take the FRUITS data into account and the median value is reported. Markers in black are new measurements. Markers in grey are recalibrated dates from Schulting and Richards (2002)



When the dietary reconstructions of all humans measured are placed in a chronological context, the data reveal an extremely interesting pattern. Figure 6.23 shows estimates of marine and terrestrial resources in the diet plotted against the radiocarbon date of each individual, calibrated using the mixed marine/terrestrial curve. The oldest samples (GU41836 and GU40827 from Cnoc Coig) show evidence of a typical late Mesolithic diet: heavily reliant on marine resources, with little or no input from the terrestrial environment. The Neolithic samples from the earliest (GU41550 from the Tulloch of Assery B) to the latest sample (GU41549 from Quoyness) show a relatively consistent and unchanging diet over the course of c.700 years that is largely made up of terrestrial resources, with some contribution from marine foods.

This contrast in diet between Mesolithic and Neolithic human bone collagen samples observed in Figure 6.23 is closely in line with what we understand to be the dietary patterns for the two periods. The findings are in close agreement with results of stable isotope analysis of teeth from children who lived in Neolithic Shetland (Montgomery, et al. 2013).

It was found by Montgomery et al. that children were periodically consuming marine resources, possibly in response to farming in a marginal environment. The results of this thesis compliment those from Shetland in that, while they are unable to demonstrate the periodic nature of the diet, they show a better resolution of food groups by distinguishing between mammals, fish and shellfish. The fact that these results and the findings from this research are similar, despite the method of investigation differing, (measurement of bulk bone collagen stable isotopes compared to sequential measurement of tooth dentine isotopes) strongly suggests that the presence of marine foods in the Neolithic must now be accepted.

Both the recent work by Montgomery et al (2013) and the work presented here contributes towards the academic debate discussed in the mid-2000s surrounding the consumption of marine resources in the Neolithic. While some research argued that stable carbon and nitrogen isotope measurements of humans from Scotland and sites in mainland Europe demonstrated a rapid change in diet during the Mesolithic-Neolithic transition that involved the complete rejection of marine resources that were heavily relied upon in the Mesolithic (Schulting and Richards, 2002, Richards et al., 2003). Others emphasised that the shell middens in the River Forth Estuary and fish remains in Orkney should not be discounted as credible evidence of dietary habits in the Neolithic (Milner et al., 2004). It was also hypothesised that humans could source up to 20% of their dietary protein from marine resources without significantly affecting their $\delta^{13}C$ values (Milner et al,2004). In their reply, Richards and Schulting (2006) argue that, for this theory to be correct, the dominant seafood in the Neolithic diet must have been shellfish, not fish. They state that, 'it is almost unnecessary to point out that such a diet is unlikely to describe the Neolithic of Denmark and Britain' (Richards and Schulting, 2006), however, the data presented in this thesis from stable isotope analysis and radiocarbon dating of human remains from multiple Neolithic sites across Scotland is very much in line with the argument outlined by Milner et al, (2004).

It seems clear that the importance of marine resources in the Neolithic have been considered in previous research, but have ultimately been downplayed, resulting in a misconception that a Neolithic diet relied solely on terrestrial foods. Schulting and Richards (2010), for example conclude that 'no discernible role' was played by marine resources in the diets of humans at Carding Mill Bay, Raschoille cave and Crarae in the west coast of Scotland. This conclusion was derived from stable isotope measurements; however, the same authors conclude that Scottish Neolithic humans with overlapping stable isotope values could have consumed up to 20% of their diet from the marine environment (Schulting and Richards, 2009). This

proportion of marine food is not a negligible amount; applying this same abundance to a modern day dietary equivalent of three meals a day amounts to a person consuming fish and shellfish in excess of four times a week. This amount was described as being 'a slight contribution' (Schulting and Richards, 2009), however it is contended in this thesis that a 20% contribution within the diet is not slight, and that marine resources were indeed an important resource in the Neolithic.

It is not only stable isotope data that has been interpreted in such a way that has resulted in generalisations regarding Neolithic diet. In a discussion regarding fishing in Neolithic Orkney, Harland and Parks (2009) noted that while butchery marks were found on the skeletal remains of terrestrial mammals at the Neolithic site of Isbister, similar marks were present on only a single cod from the Holm of Papa Westray. Their conclusion was that 'this may suggest that prepared food on these occasions extended to fish', although this remark was then tempered by observing that fish could also have been deposited by otters (Harland and Parks, 2009). What isn't considered when discussing the viability of Neolithic fishing is that the patterns seen in the faunal assemblages at Isbister and the Holm of Papa Westray are expected because of taphonomic issues related to fish remains. Mammal remains are far more robust and therefore the bones and the butchery marks are better preserved in archaeological examples than in fragile fish bone. In addition to preservation biases, fish bones are only reliably recovered on sites that employ sieving. Finally, butchery techniques for fish are very different to those employed on, for example, a joint of meat. While butchery cut marks on animals such as cattle are commonly present on well preserved and diagnostic long bones, butchery marks on fish remains are more likely to be present on fragile and undiagnostic rib bones; these elements are often damaged in post-depositional handling or are overlooked during zoological analysis (Willis et al., 2008). Therefore, the absence or relative scarcity of fish bone or the absence of butchery marks on fish bone cannot be used to argue that fish were not consumed on any given archaeological site.

The findings of this research address concerns made by Milner and Craig (2009) regarding the accuracy of radiocarbon dates from sites along the west coast of Scotland and the Hebrides. Many of the sites in Milner and Craig's study have been re-examined here: they analysed samples from Carding Mill Bay, Raschoille cave and Cnoc Coig. When attempting to characterise the chronology of activity and funeral rites at each of the sites, they expressed concerns surrounding regional ΔR values, unreliable 100% marine and terrestrial dietary end-point values, and an ambiguity surrounding the characterisation of marine resources in

the diet (Milner and Craig, 2009). By taking into account the appropriate ΔR values for each site, by characterising the faunal baseline at each site and by using the archaeological evidence to inform Bayesian modelling, the results presented here show that the chronology of all the sites in this thesis are indeed secure.

6.5 The Wider Implications and Further Recommended Research

In addition to the new information about human diet and chronology in the Scottish Neolithic, this research has implications for several aspects of the current knowledge regarding stable isotope dietary studies, and the relationship between populations in the Scottish Neolithic. There are also further questions which arise from the data, necessitating the proposal of new research with minor changes in focus.

It has become increasingly clear in recent years that researchers are beginning to understand the importance of a representative faunal baseline in stable isotope dietary studies. Mulville et al. (2009), Cook et al. (2015) and Charlton et al. (2016) have all argued that careful consideration of food sources is crucial to accurate dietary reconstruction. However, there is a lack of research to date which addresses the best method to construct a faunal baseline when faunal remains are not found at the same archaeological site as human remains. This thesis has attempted to address this gap in our knowledge by exploring the viability of using modern samples to supplement insufficient faunal baselines in the context of Neolithic Scotland.

Modern marine fauna were found to be suitable analogues for ancient samples. Because there is no isotopic difference between modern and ancient marine isotope values, modern samples are suitable for inclusion in stable isotope dietary study at sites in Scotland regardless of time period. It is hypothesised that these is the case because the ocean is such a large and mixed environment that has not been as heavily influenced by anthropogenic activity as the terrestrial environment. Being able to include modern marine samples in ancient baselines is beneficial to archaeological investigation as fish bones are rarely available for isotopic sampling due to preservation and sample excavation biases. This finding could also be applied to sites outside of Scotland, but further work is required to investigate whether Scotland is unique in having preserved its marine carbon and nitrogen isotope signatures over thousands of years.

In contrast to marine fauna, modern terrestrial samples were not suitable as analogues for ancient samples. For the most part; however, modern samples did not originate from the same sites as the archaeological fauna. This meant that it was not possible to compare spatially matched modern and ancient samples. The modern terrestrial samples had to be grass fed animals, sourced from completely organic farms and this proved difficult as most organic farms supplement their animals' diet with a mixed grain feed which is not locally produced. In order to conclusively measure whether modern terrestrial samples are suitable for inclusion in ancient faunal isotope baselines, we must identify the modern samples first and then source archaeological fauna (regardless of period) to compare them against. This will result in a proof of concept study to test whether modern terrestrial mammals are appropriate analogues in ancient stable isotope baselines. If this proves successful, then we can begin to apply the theory to Scottish Neolithic sites.

This thesis showed that, although there is some regional variation in individual food sources, Neolithic communities across Scotland sourced c.20% of their protein from the marine environment. This equates to up to 1091 years of dietary stability, considering the earliest and latest Neolithic radiocarbon dates in this research (3766 to 2675 cal BC). This observation results in questions that are beyond the scope of this research, but are worth considering as future directions in research, namely: Is there a link between dietary stability and cultural continuity of technology in the Neolithic? Is this dietary stability replicated elsewhere in Neolithic Europe and is it unique to the time period? Further work which combines stable isotope analysis with consideration of evidence of material culture, for example change in lithic and pottery forms over time, will begin to address these questions.

We can also begin to explore the implications behind the dietary stability observed during this research. Very similar dietary patterns were observed across the Neolithic sites examined. This general dietary homogeneity can be linked to Neolithic mobility and the extent to which Neolithic communities were connected in Scotland. The findings here about diet suggest that Neolithic communities in Scotland were able to communicate with each other, either by passing on ideas or by being physically mobile. If Neolithic communities were isolated, we would expect to see far more variation in the diet as each group developed their own subsistence strategies. The Neolithic lifestyle has, in the past, been characterised as sedentary; however, we understand today that Neolithic people in Britain were far more mobile than originally thought (Neil et al., 2016). This relatively new understanding of Neolithic lifestyle compliments and supports the findings about diet seen in this thesis.

Related to the subject of the mobility of people is the mobility of animals. A small amount of sulfur isotope measurements made on fauna from three sites in the west coast of Scotland (Carding Mill Bay, Risga and Ulva) and one site in Orkney (Pool) indicated that the animals were likely to have been raised locally (see Table 5.29). Considering that the dietary patterns in this thesis demonstrates some mobility of people or ideas, it is interesting that the animals that were investigated appear to have stayed on coastal sites throughout their lives. While the sulfur values do not discount the movement of animals along the coastline, they may demonstrate the permanent 'homestead' of Neolithic communities: while people and ideas may have been mobile, permanent settlements which communities occupied were an important feature of the Neolithic lifestyle.

Finally, this research has implications beyond the study of the Mesolithic and Neolithic periods in Scotland. The findings here show that, despite the detection of small amounts of marine resources in the human diet, this does not significantly affect the accuracy of the radiocarbon dates of these individuals as a result of potential MREs. This is important because both anecdotally and in the literature (e.g. Barrett et al., 2000, Cook et al., 2002, Yoneda et al., 2002) it is often implicitly assumed that a marine component to the diet would have significant implications for radiocarbon dating. The research presented in this thesis; however, shows definitively that this is not the case. This is not to say that it is not important to fully and properly assess human diet in radiocarbon dated bone collagen. Indeed, to get a proper assessment of the precision on dates, marine foods must be considered where there is on-site evidence for their inclusion in the diet. The calculate age range of the majority of the radiocarbon dates of human samples increased following assessment using stable isotope analysis and FRUITS dietary reconstructions. This shows that where marine contributions to the diet are not properly considered, the radiocarbon dates of those individuals are likely to be erroneously precise. This is the case for human remains from any period and any archaeological site across the world.

Chapter 7: Conclusion

7.1 Summary of Conclusions

The overarching aim of this thesis was to increase the depth of knowledge surrounding changes to the diet across the Scottish Mesolithic/Neolithic transition. Specifically, this research contributes towards the debate in archaeology surrounding the importance of marine resources in the Neolithic in Scotland. This contribution was achieved via the novel application of the isotope Bayesian mixing model, FRUITS to modern and archaeological fauna in order to recreate human diet from bone collagen isotope measurements.

The results of this research have archaeological implications, as well as contributing towards improving the methodology employed when using stable carbon and nitrogen isotope analysis for dietary reconstruction. The key finding relating to ancient diet was that modest amounts of marine resources were consumed by Neolithic communities across Orkney Islands and the west coast of Scotland. Conclusions that could be drawn from the results about stable isotope analysis were that modern marine fish and shellfish were suitable for inclusion in ancient dietary baselines, and that FRUITS can be used to distinguish between the relative abundance of fish and shellfish in the diet.

7.2 Exposition of Conclusions

The following section breaks down the overarching finding of this research into detailed conclusions and recommendations; there are eight in total:

1. When estimating ancient diet using stable isotope analysis, it is essential to use all available evidence of likely food sources that are present within the archaeology as skeletal or shell remains. Stable isotope analysis of human bone collagen, while an extremely useful analytical technique, can only provide very broad indications of diet. Where there is some discrepancy between the isotope data and the archaeological evidence (as seen at the sites presented in this thesis), Bayesian tools such as FRUITS and prior information from the associated faunal assemblage is extremely beneficial to bring some accuracy and precision

to dietary reconstructions. To this end, we must strive to think of stable isotope analysis as an archaeological tool and not as a distinct analytical technique.

2. One of the most pressing issues surrounding the accurate interpretation of human bone collagen isotope data for dietary reconstruction is a lack of proper consideration of dietary isotope baselines. Mesolithic and Neolithic archaeological assemblages from Scotland are generally lacking in the appropriate samples required to create good quality baselines. This is especially true of fish and shellfish remains: there are many instances where evidence of these dietary food groups are recorded on-site, but are either not sufficiently recovered or are not available for analytical investigation. Building an adequate shellfish baseline is also problematic since only the inorganic shells are preserved, and these are not conducive to isotopic investigation for dietary reconstruction. This research has shown that, given proper consideration of the relevant offsets (see conclusion 4 in this chapter), modern marine fish and marine shellfish can be utilised to supplement an ancient dietary baseline. This finding could potentially enable researchers in Scottish archaeology to confidently investigate diet at sites of any time period where there is evidence for marine consumption, but a lack of suitable samples.

3. While the need to bolster terrestrial sample sizes in dietary baselines are not as pressing as the need to supplement ancient marine baselines, the ability to include modern analogues here would have been useful. The remains of terrestrial animals, particularly large species such as cattle and deer that were commonly consumed in the Mesolithic and Neolithic, are often well preserved in comparison to fish skeletal remains. This means that, in theory, these remains should be plentiful; in some cases this is true, such as at Carding Mill Bay and Risga which both had extensive faunal assemblages to sample from. The majority of sites in this thesis; however, had much smaller assemblages or had no assemblage available to sample from. While all reasonable efforts were made to build appropriate terrestrial baselines, there were some instances, such as at Loch Borralie, where there was no suitable faunal assemblage to draw a baseline from. In cases such as this, country-wide average stable isotope values were used to represent the baselines, with the caveat that the interpretations that resulted would not be entirely secure. It would have been advantageous, therefore, if it

were possible to supplement ancient terrestrial dietary baselines with modern samples, as had proved successful in the case of marine fish and shellfish.

The findings of this thesis suggest that modern terrestrial herbivores are, in fact, not suitable as analogous sample for ancient bone collagen. Stable isotope measurements of modern and ancient species equivalents were not comparable and were not utilised in the dietary reconstructions of Mesolithic and Neolithic humans using FRUITS. The likely reason behind this is that anthropogenic influences on animal diets and the environment that they subsist in have resulted in differences in isotope values of modern domestic animals and ancient wild and domestic animals. It must be noted; however, that it was difficult to locate samples that were from the same locations as the archaeological sites studied here and the majority of modern samples came from geographically incomparable sources. In order to be confident that modern terrestrial fauna are not suitable samples for inclusion in ancient dietary studies, modern samples would have to be matched with an ancient population from the same geographic region. Further work has therefore been proposed to fully investigate the viability of modern terrestrial samples.

4. Isotope offsets must be well-defined and appropriately applied where necessary in stable isotope dietary studies. Offsets for consideration include the Suess Effect offset which affects the carbon isotope measurements of modern and ancient fauna, the tissue offset between faunal flesh and bone which provides the 'food groups' value in FRUITS, and the offset between these food groups and human bone collagen. The latter value is difficult to quantify, given that studies would have to use living human participants in order to acquire known values of human bone collagen and diet.

5. When recreating ancient diet using stable isotope analysis, and where the archaeological evidence points towards both fish and shellfish being contributors to the diet, it is recommended that FRUITS is employed when interpreting the data. This work has shown that FRUITS is capable of distinguishing between the relative abundance of fish and shellfish. This is both an original demonstration of the capabilities of FRUITS, as well as an improved method of interpreting stable isotope results. This is in comparison to the traditional method of plotting human bone collagen isotope measurements on a bivariate plot

and comparing the offset between the humans and measurements of faunal bone collagen isotope data, which is the most common method of interpretation.

6. The stable isotope and radiocarbon data show that the long term dietary habits of individuals whose remains dated between 3776 and 2869 cal BC were comparable. This is remarkable, since the sites that were investigated were from a large geographic area across Scotland. The similarity of Neolithic diets between the west coast of Scotland and Orkney suggest some physical connection between people across the country at this time. If communities were isolated and non-communicative, distinct diets would be expected to emerge over such considerable geographic distances. This finding warrants further study to investigate the spatial and chronological boundaries of this homogeneity in the Scottish Neolithic diet.

7. Marine resources were a small contributor to the diet in Neolithic Scotland. While there was a significant shift from a heavily marine based diet in the Mesolithic to one reliant on terrestrial resources in the Neolithic, fish and shellfish remained a feature of the Neolithic diet. This finding is supported by archaeological evidence on all of the sites investigated here; namely that the presence of small amounts of fishbone and larger proportions of shellfish remains in food middens indicates that they were consumed by the communities that created them. This finding is also unsurprising, given that all sites in this thesis were located near the coast: it seems plain that communities living by the sea would exploit the food that was available.

8. We can be confident in the chronology of the Scottish Mesolithic-Neolithic transition provided by existing radiocarbon dates. It was suspected at the beginning of this research that hereto undetected marine carbon in bone collagen samples would shift radiocarbon dates due to the marine reservoir effect. Upon detection of marine resources and recalibration of radiocarbon dates using this information, the predicted shift was not observed. Up to 21±14‰ (OxA7890 at Carding Mill Bay) marine input in the diet resulted in a larger range in the predicted radiocarbon date, but did not alter the date itself. This is not to say that recalibration of past dates is not required. For the most accurate dates, diet should be fully

assessed using an appropriate and representative dietary baseline, known tissue offsets and a suitable mixing model. Accurate dietary information must then be used when calibrating dates in Oxcal. This will result in dates that are more accurate, but have less precision than dates where diet has not been properly considered. It is asserted by the author that greater accuracy should be sought over improved precision as data that is highly precise, but incorrect, is ultimately unhelpful and potentially misleading.

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Appendix A: Publication in Radiocarbon

The following manuscript was published in the journal, Radiocarbon, as part of the 2016 Radiocarbon and Archaeology Conference special issue.

Radiocarbon, Vol 59, Nr 5, 2017, p 1275–1294 DOI:10.1017/RDC.2017.39

USING STABLE ISOTOPES AND A BAYESIAN MIXING MODEL (FRUITS) TO INVESTIGATE DIET AT THE EARLY NEOLITHIC SITE OF CARDING MILL BAY, SCOTLAND

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ABSTRACT. We present $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ measurements on archaeological human and animal bone collagen samples from a shell midden dating to the Neolithic ca. 4000 3500 cal BC, together with measurements on modern fish and shellfish. These data were used in conjunction with the Bayesian mixing model, Food Reconstruction Using Isotopic Transferred Signals (FRUITS), to reconstruct human diet at the site. We demonstrate the importance of using a geographically appropriate faunal baseline in stable isotope paleodietary studies, and suggest that Neolithic individuals at this site consumed up to ca. 21% of dietary protein from marine resources, despite stable isotope ratios that imply a wholly terrestrial diet. This marine resource consumption does not significantly shift the radiocarbon (^{14}C) dates of these individuals, so although we must consider the use of marine resources at the site, the chronology that has previously been established is secure. The $\delta^{13}C$ and $\delta^{15}N$ measurements from the archaeological herbivore bone collagen indicate that it is unlikely they ate plants enriched with fertilisers such as manure or seaweed. The $\delta^{34}S$ values reveal a sea-spray effect; therefore, in this instance, $\delta^{34}S$ cannot be used as a dietary indicator but can be used to demonstrate the likely locality of the fauna.

KEYWORDS: stable isotopes, paleodiet, Mesolithic, Neolithic, Scotland.

INTRODUCTION

The Mesolithic-Neolithic transition marked a profound shift in socioeconomic patterns, which is represented in the archaeological record by stark changes in material culture and subsistence practices. The Neolithic brought a fundamental change in human lifestyle, reflected in the introduction of farming, new technology including pottery and ground stone artifacts, and distinctive forms of architecture and burial practice.

The nature and timing of the Mesolithic-Neolithic transition remains a much-debated topic in archaeology. Recent aDNA studies have shown that early farmers in central and southwestern Europe show a genetic affinity to populations in the Near East, with the implication that demographic expansion and migration played an important role in the appearance of the Neolithic in these regions, although an admixture with local foragers is also indicated (e.g. Haak et al. 2010; Olalde et al. 2015). Palaeogenetic research into the transition in the British Isles is less advanced and archaeological opinion is still divided over whether colonisation from mainland Europe (Sheridan 2010) or indigenous adoption (Thomas 2008) was the main driver of Neolithization.

Regardless of the eventual outcome of the debate over the nature and timing of the transition in the British Isles, it is pertinent that we seek answers to more detailed questions about human lifestyle at this key juncture in prehistory. The extent of dietary change associated with the Mesolithic-Neolithic transition in Scotland is one such question that remains controversial. Stable isotope analysis for dietary reconstruction has been employed to investigate these changes (Richards and Mellars 1998), but is constrained by the scarcity of Mesolithic human remains from Scotland. Evidence of a chronological overlap in Mesolithic and Neolithic

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lifestyles comes from the shell midden of Cnoc Coig, Oronsay, which is usually attributed to the Late Mesolithic. Charlton et al. (2016) used ZooMS, stable isotope analysis and radiocarbon (^{14}C) dating to identify two human bones from the midden with stable carbon and nitrogen isotope values that reflect the consumption of a significant amount of marine protein, and ^{14}C dates that overlap with those on human remains from other parts of western Scotland that exhibit more terrestrial diets (Richards and Sheridan 2000; Schulting and Richards 2002). These data could be interpreted to indicate that the Cnoc Coig individuals were Mesolithic hunter-gatherers who coexisted with agricultural communities. This highlights the fact that there is insufficient archaeological or other evidence to support a rapid and total abandonment of marine resources in the Early Neolithic, a point emphasized by Milner et al. (2004).

Several stable isotope and lipid biomarker studies have been used to argue for a rapid and permanent shift in Scotland from a diet rich in marine protein in the Mesolithic, to one wholly reliant on terrestrial resources in the Neolithic (Richards et al. 2003; Richards and Schulting 2006; Cramp et al. 2014). However, issues with using stable isotope analyses to detect potentially much more subtle changes in diet have been highlighted by Milner et al. (2004), Bonsall et al. (2009), and Charlton et al. (2016); namely that the use of linear interpolation between terrestrial and marine δ^{13}C end-members to estimate marine resource consumption in humans has a large error of up to 20%, and that faunal baselines must be better defined when dealing with humans that may have consumed marine resources. The present study seeks to address both issues.

Our knowledge of the transition is somewhat hindered by the fact that δ^{13}C and δ^{15}N isotope analysis of bulk bone collagen is the most cost effective method of estimating individual diets, but the resolution is poor as it gives an average of food sources consumed over 5–10 years or more before the subject's death, depending on which bone is sampled (Sealy et al. 1995; Richards and Hedges 1999). In comparison, the incremental dentine method (Beaumont et al. 2013), which was employed by Montgomery et al. (2013) to detect periodic returns to marine resources by Scottish Neolithic individuals, picks up relatively short-lived changes in eating habits, but only while the teeth are forming. Alternative approaches to reconstructing diet have been utilized in response to the issues associated with analyzing human bone collagen. For example, Cramp et al. (2014) used lipid biomarkers to detect dairy products in Neolithic pot sherds from the Outer Hebrides. In the absence of marine biomarkers, they concluded that dairying completely replaced fishing in the Neolithic. However, the technique can only inform on food cooked in pots (as opposed to on an open fire, for example) and cannot recreate the diet of individual people. Currently, the bulk bone collagen isotopic evidence of diet in the Neolithic in Scotland appears at odds with the archaeological evidence. δ^{13}C and δ^{15}N isotope measurements on human bone collagen have been interpreted as indicating an almost complete abandonment of marine resources (Richards et al. 2003; Richards and Schulting 2006), yet Neolithic middens contain evidence of shellfish and fish consumption (Connock et al. 1991). We must therefore seek to reconcile the isotopic and archaeological evidence.

The study of the transition from a nomadic hunter-gatherer-fisher lifestyle to sedentary farming in Scotland is greatly hampered by the scarcity of human and animal remains that survive in the archaeological record. Some dietary resources, such as shellfish are well represented, but the edible organic portion has either been consumed or totally degraded, leaving only the inorganic shells. Organic remains are vital for reconstructing ancient diets and subsistence practices, and for placing these in a secure chronological context. Issues surrounding human diet and lifestyle are particularly pressing in Scotland due to the coastal setting of many of the surviving sites: it is important that these particularly vulnerable sites are recorded and interpreted before they are lost to climate change and erosion.

The scarcity of suitable bone samples, resulting in unrepresentative dietary baselines in stable isotope studies, is not a problem that is unique to Scotland. Very few stable isotope studies take into account all available food sources when reconstructing diet because of the limited availability of samples to measure. Baselines are constructed from the faunal remains found on site but do not consider foods that may have been lost to degradation. Other studies use non-local faunal remains in an attempt to fill baseline gaps, but overlook that one of the fundamental reasons for building a baseline is to correct for natural geographical variations in isotope values that are reflected in every stage of the food-chain (Peterson and Fry 1987). In addition, very small quantities of marine resources in a diet dominated by terrestrial resources are difficult to discern using the traditional stable isotope bivariate plot (e.g. Bonsall et al. 2009). These plots can give a broad indication of dietary habits by examining human isotope values in relation to a faunal baseline. However, relative contributions from different dietary sources cannot be calculated, and no meaningful statistical error can be placed upon dietary estimations. Linear interpolation, using $\delta^{13}C$ measurements and theoretical 100% marine and terrestrial human diet $\delta^{13}C$ end-members, has been utilized as a tool to calculate the abundance of marine protein in the diet (Arneborg et al. 1999; Cook et al. 2015). However, these end-points are commonly derived from populations that may not be relevant to the study and may not be representative of human diets in geographically diverse locations. To detect subtle variations in past diets using bulk bone collagen isotope analysis, we must use geographically relevant samples and interpret the data using models that provide more accurate dietary estimates.

This work used Food Reconstruction Using Isotopically Transferred Signals (FRUITS), a Bayesian mixing model developed by Fernandes et al. (2014) as a tool for reconstructing past human diets. The model works by comparing a mixed target to several isotopically unique sources and calculating the most probable relative contribution each source has made to form the target. The model can be can be used with or without added Bayesian priors. To produce accurate human dietary reconstructions using FRUITS, it is necessary to specify the dietary isotopic baseline values as "food values." These are specified as the values of the food that was consumed, as opposed to the traditionally used faunal bone collagen values, because of the isotopic offset between flesh and bone (Peterson and Fry 1987). However, little consensus exists as to what the correct offsets are and whether they vary between species. The baseline values are specified because natural geological isotope values can vary, and these variations are reflected throughout the food chain from soil/ocean minerals to plants, to herbivores, to carnivores and omnivores. To obtain the correct baseline, it is important to measure the stable isotope values of fauna from the same context as the humans whose diet is being reconstructed. This gives the most accurate baseline values for FRUITS and, indeed, any other method of stable isotope dietary reconstruction.

Carding Mill Bay is a Neolithic shell midden on the west coast of Scotland (Figure 1). The midden contained a variety of faunal and some human remains within a matrix of marine shells dominated by limpets (*Patella* spp.). Radiocarbon dating places the midden in the period between 4000 and 3500 cal. BC (Connock et al. 1991; Bronk Ramsey et al. 2000). The midden was excavated by Lorn Archaeological Society and finds analysis was carried out by Historic Environment Scotland. Finds included bones of birds, terrestrial mammals (wild herbivores and pig) and marine fish, together with a range of lithic and bone artifacts (Connock et al. 1991). Disarticulated human remains were recovered from several contexts of the midden (IV, VII, X, XIV, XV, and XXIII) and from a cist burial in contexts II and III (Connock et al. 1991). The site has been the subject of several later studies investigating the Scottish Neolithic because of the presence of both human and animal remains as well as "Obanian" artifacts, which are

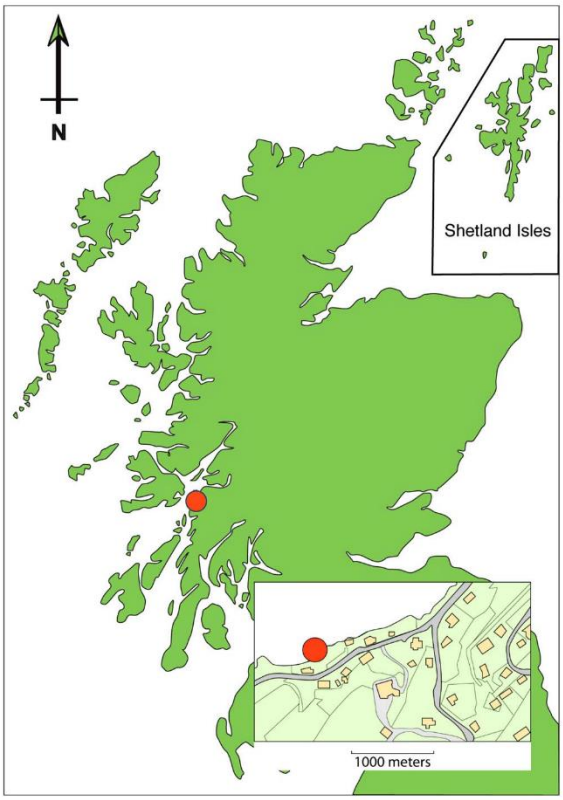

Figure 1 Location of Carding Mill Bay in Scotland.

characteristic bevel ended antler or bone tools, often found in the absence of retouched stone tools (Schulting and Richards 2002; Bartosiewicz et al. 2010).

The work we present here sought to better understand the dietary changes that occurred during the Mesolithic-Neolithic transition in western Scotland, using $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ isotope measurements on bone collagen from human and animal remains from Carding Mill Bay. Given the sparse character of the faunal assemblage from this site, we tested the hypothesis that modern marine and terrestrial analogs could be used to supplement the ancient archaeological dietary baseline. To ensure the correct values were used in the FRUITS models, we used a local baseline, and measured species-specific $\Delta^{13}C_{\text{muscle protein-bone collagen}}$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}}$ offset values in three marine and four terrestrial species. These values were used to model the diet of four human individuals from the midden whose isotope measurements were previously interpreted to be indicative of a wholly terrestrial diet (Schulting and Richards 2002).

It is well known that the calibration of samples containing marine carbon must take account of the marine reservoir effect (MRE) and that ΔR values (representing the local offset from the global average surface water MRE at a point in time) in Scotland show spatial variability

(Ascough et al. 2004; Cook et al. 2015). Given the uncertainty surrounding marine consumption in the early Scottish Neolithic, a further reason for estimating the marine contribution at Carding Mill Bay was to reassess published ^{14}C dates at the site to take these MREs into account and report more accurate dates for the human samples. This necessitates a calculation of the Carding Mill Bay ^{14}C reservoir offset value (ΔR) and the proportion of marine carbon contributing to the human bone collagen.

To place the site and the human remains in a more secure chronological context, two contexts were chosen for the determination of new ΔR values. The multiple paired marine-terrestrial sample approach was adopted (Ascough et al. 2009; Russell et al. 2015) together with χ^2 testing (cf. Ward and Wilson 1978) to ensure that the groups of marine and terrestrial samples were internally, statistically indistinguishable. The two contexts chosen for analysis were XIV and XV. Carding Mill Bay has a range of quoted ΔR values (see Table 11), however, the values calculated by Reimer et al. (2002) were based on single pairs of samples and since the terrestrial samples employed were charcoal, which can produce anomalously old ages because of the potential for an old wood effect, we made the decision not to use these. The value calculated by Ascough et al. (2004) was identified as an outlier in the complete dataset: this may be because the ^{14}C ages of terrestrial samples fell into two distinct groups and the correct offset was therefore difficult to determine. In light of this, improved values were sought using terrestrial herbivore bone collagen.

METHODS

Archaeological samples from the midden were provided by Glasgow Museums Research Centre and included 16 samples of at least three terrestrial species including red deer (*Cervus elaphus)*, large mammals [cattle (*Bos taurus*), and/or red deer (*Cervus elaphus*)], and medium mammals [sheep (*Ovis aries*) and/or roe deer (*Capreolus capreolus*)], to form the isotope baseline for the terrestrial fauna from the site. Contexts with human remains were targeted—see Table 1. As there were no fish bones available to sample from Carding Mill Bay, the ancient marine fish baseline was derived from measurements of Viking Age/Medieval cod from Orkney and Caithness (Russell 2011). Marine fish are highly mobile and this results in very little variation in isotope measurements of fish caught anywhere off the coast of Scotland (Barrett et al. 2008). Therefore, the fish from Orkney were deemed suitable analogs for fish caught at Oban. Modern terrestrial herbivore analogues came from organic farms in Perth and Dumfries (Table 2) Modern marine samples included three species of fish [cod (*Gadus morhua*), haddock *(Melanogrammus aeglefinus*) and pollock (*Pollachius pollachius*)] from the North Sea (Table 3) and four species of shellfish: cockles (*Cerastoderma edule*), limpets (*Patella vulgata*), mussels (*Mytilus edulis*), and winkles (*Littorina littorea*) from the Oban area (Table 4).

Modern bone samples were split into two fractions: an untreated fraction and a lipid extracted fraction. The lipid-extracted fraction was prepared as follows: each sample was crushed and solvent extracted in a sonic bath for 30 minutes using 2:1 DCM:MeOH (Dichloromethane: Methanol) followed by MeOH and finally with reverse osmosis water until traces of organic solvent were removed. Collagen was extracted from the lipid-free bone and the bone containing lipids. Ancient faunal bone samples were prepared using the standard SUERC bone collagen pretreatment method with ultrafiltration to remove degraded collagen and other contaminants (Dunbar et al. 2016). Shellfish flesh was Soxhlet extracted for 7 hr using 2:1 DCM:MeOH followed by 7 h using MeOH. The samples were then thoroughly soaked and washed several times with reverse osmosis water to remove residual organic solvent. Samples for stable isotope

Table 1 Ancient faunal bone collagen isotope measurements—terrestrial samples from Carding Mill Bay, marine samples from Roberts Haven and Quoygrew (Russell 2011).

Sample ID	Species	Context nr	$\delta^{13}C_{VPBD}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	C/N atomic ratio	$\delta^{34}S_{CDT}$ (‰)	C/S atomic ratio	N/S atomic ratio
GUsi-3497	Medium mammal *(Ovis aries or Capreolus capreolus)*	VI	–21.6	+3.5	3.2	+18.7	619	192
GUsi-3498	Large mammal *(Cervus elaphus* or *Bos taurus)*	IV	–23.3	+3.4	3.2	+20.8	661	207
GUsi-3500	Large mammal *(Cervus elaphus* or *Bos taurus)*	IX	–22.8	+2.8	3.5	+19.6	441	127
GUsi-3501	Large mammal *(Cervus elaphus* or *Bos taurus)*	IX	–23.1	+3.1	3.5	N/A	N/A	N/A
GUsi-3502	Large mammal *(Cervus elaphus* or *Bos taurus)*	IX	–22.8	+2.8	3.6	+20.0	533	149
GUsi-3503	Large mammal *(Cervus elaphus* or *Bos taurus)*	VII	–22.5	+2.7	3.4	+19.9	409	121
GUsi-3504	Large mammal *(Cervus elaphus* or *Bos taurus)*	XIV	–22.5	+3.1	3.2	+20.3	580	181
GUsi-3505	Large mammal *(Cervus elaphus* or *Bos taurus)*	XIV	–23.2	+3.7	3.3	N/A	N/A	N/A
GUsi-3506	Large mammal *(Cervus elaphus* or *Bos taurus)*	XIV	–22.5	+2.4	3.2	+21.0	699	218
GUsi-3507	Medium mammal (Ovis aries or *Capreolus capreolus)*	XIV	–22.9	+3.7	3.2	+20.1	560	173
GUsi-3508	Large mammal *(Cervus elaphus* or *Bos taurus)*	XIV	–23.2	+2.3	3.2	+20.9	712	223
GUsi-3509	Red deer *(Cervus elaphus)*	XVII	–23.2	+3.0	3.4	+20.3	561	167
GUsi-3511	Large mammal *(Cervus elaphus* or *Bos taurus)*	XIV	–22.8	+3.9	3.2	N/A	N/A	N/A
GU-18879	Cod *(Gadus morhua)*	3004	–14.7	+13.5	4.0	+16.2	233	58
GU-18880	Cod *(Gadus morhua)*	3004	–14.1	+15.3	3.8	+15.9	183	48
GU-18881	Cod *(Gadus morhua)*	3004	–13.7	+13.7	3.7	+16.0	199	54
GU-18882	Cod *(Gadus morhua)*	3004	–13.4	+13.9	3.6	+15.8	207	57
GU-18883	Cod *(Gadus morhua)*	3019	–14.4	+15.0	3.6	+16.5	181	51
GU-18884	Cod *(Gadus morhua)*	3019	–12.5	+13.1	3.5	+15.9	206	59
GU-18885	Cod *(Gadus morhua)*	3019	–13.3	+15.3	3.4	+16.1	197	57
GU-18886	Cod *(Gadus morhua)*	3019	–13.3	+14.0	3.4	N/A	N/A	N/A
GU-18887	Cod *(Gadus morhua)*	A004	–12.9	+13.9	3.5	+16.5	210	61
GU-18888	Cod *(Gadus morhua)*	A004	–14.3	+13.7	3.6	+16.9	236	67
GU-18889	Cod *(Gadus morhua)*	A004	–14.2	+14.9	3.5	+17.0	160	44
GU-18890	Cod *(Gadus morhua)*	A004	–13.7	+13.7	3.5	+16.9	282	80
GU-18891	Cod *(Gadus morhua)*	A023	–12.4	+14.4	3.3	+17.1	211	60
GU-18892	Cod *(Gadus morhua)*	A023	–13.0	+13.6	3.4	+16.9	135	41
GU-18893	Cod *(Gadus morhua)*	A023	–13.4	+13.1	3.3	+16.8	226	66
GU-18894	Cod *(Gadus morhua)*	A023	–13.0	+13.8	3.4	+16.8	179	54

Table 2 Modern inland terrestrial herbivore isotope measurements.

Species	Nr of samples	Tissue fraction	Average $\delta^{13}C_{VPDB}$ value (‰)	Average $\delta^{15}N_{AIR}$ value (‰)
Cattle *(Bos taurus)*	3	Bone collagen	–24.9 ± 0.2	+6.4 ± 0.7
Cattle *(Bos taurus)*	3	Bone collagen including lipids	–24.7 ± 0.0	+6.2 ± 0.1
Cattle (Bos taurus)	3	Muscle protein	–26.6 ± 0.1	+5.4 ± 0.6
Sheep *(Ovis aries)*	6	Bone collagen	–25.5 ± 0.6	+7.3 ± 0.7
Sheep *(Ovis aries)*	6	Bone collagen including lipids	–25.6 ± 0.2	+7.6 ± 0.5
Sheep *(Ovis aries)*	6	Muscle protein	–27.8 ± 0.1	+7.7 ± 0.5
Red deer *(Cervus elaphus)*	10	Bone collagen	–24.5 ± 0.3	+3.4 ± 0.8
Red deer *(Cervus elaphus)*	10	Bone collagen including lipids	–24.4 ± 0.3	+3.6 ± 0.7
Red deer *(Cervus elaphus)*	10	Muscle protein	–26.1 ± 0.3	+3.7 ± 0.6
Roe deer *(Capreolus capreolus)*	9	Bone collagen	–24.9 ± 0.6	+4.9 ± 1.1
Roe deer *(Capreolus capreolus)*	9	Bone collagen including lipids	–24.7 ± 1.0	+4.8 ± 1.4
Roe deer *(Capreolus capreolus)*	9	Muscle protein	–27.1 ± 0.5	+5.5 ± 1.3

analysis were freeze-dried and measured using a Costech ECS 4010 elemental analyzer coupled via a Thermo Scientific Conflo IV to a Thermo Scientific Delta V Advantage continuous-flow isotope ratio mass spectrometer. For $\delta^{13}C$ and $\delta^{15}N$ measurements, approximately 600 µg of solid samples were measured alongside gelatine and tryptophan standards. For $\delta^{34}S$ measurements, 10 mg of solid samples were measured alongside cysteine, sulphanilamide, and methionine standards.

For determination of the MRE, eight terrestrial herbivore bone collagen samples (four from each of the two contexts) were combusted in sealed quartz tubes and 3 mL samples of the CO_2 were purified cryogenically, graphitized via zinc and iron reduction (Slota et al. 1987) and ^{14}C dated by AMS measurement on the SUERC National Electrostatics Corporation 5MV tandem AMS instrument. For limpet shell samples (again four from each of the two contexts), surface contaminants were removed by first manually cleaning in water and then in a sonic bath within a beaker of water. They were then reacted with 1M HCl to remove the outer 20%. The shells were dried, ground, and 0.1 g subsamples placed in hydrolysis units, where a further 20% was removed using 1M HCl immediately before full hydrolysis of the remaining material. Finally, the shell was hydrolyzed, the CO_2 extracted under vacuum and cryogenically purified. 3 mL subsamples of CO_2 were graphitized via zinc and iron reduction before AMS measurement as described above.

Table 3 Modern local marine fish isotope measurements.

Species	Nr of samples	Tissue fraction	Average $\delta^{13}C_{VPDB}$ value (‰)	Average $\delta^{15}N_{AIR}$ value (‰)
Haddock *(Melanogrammus aeglefinus)*	10	Bone collagen	–14.6 ± 0.2	+12.4 ± 0.6
Haddock *(Melanogrammus aeglefinus)*	10	Bone collagen including lipids	–14.5 ± 0.4	+12.4 ± 0.6
Haddock *(Melanogrammus aeglefinus)*	10	Muscle protein	–17.3 ± 0.2	+12.7 ± 0.8
Cod *(Gadus morhua)*	10	Bone collagen	–15.1 ± 0.8	+13.4 ± 0.5
Cod *(Gadus morhua)*	10	Bone collagen including lipids	–17.4 ± 0.8	+13.4 ± 0.5
Cod *(Gadus morhua)*	10	Muscle protein	–17.8 ± 0.3	+13.9 ± 0.3
Pollock *(Pollachius pollachius)*	10	Bone collagen	–15.9 ± 0.8	+9.6 ± 0.4
Pollock *(Pollachius pollachius)*	10	Bone collagen including lipids	–16.6 ± 0.8	+9.5 ± 0.3
Pollock *(Pollachius pollachius)*	10	Muscle protein	–18.6 ± 0.7	+12.7 ± 0.8

Table 4 Modern local marine shellfish isotope measurements.

Species	Nr of samples	Tissue fraction	Average $\delta^{13}C_{VPDB}$ value (‰)	Average $\delta^{15}N_{AIR}$ value (‰)
Limpet *(Patella vulgata)*	13	Muscle protein	–15.6 ± 0.5	+7.6 ± 1.0
Limpet *(Patella vulgata)*	13	Whole muscle	–16.6 ± 0.7	+6.9 ± 0.8
Blue mussel *(Mytilus edulis)*	8	Muscle protein	–16.9 ± 0.3	+9.2 ± 0.2
Blue mussel *(Mytilus edulis)*	8	Whole muscle	–18.4 ± 0.6	+8.7 ± 0.2
Cockle *(Cerastoderma edule)*	11	Muscle protein	–17.1 ± 0.5	+9.6 ± 0.4
Cockle *(Cerastoderma edule)*	11	Whole muscle	–17.8 ± 0.5	+9.4 ± 0.5
Winkle *(Littorina littorea)*	16	Muscle protein	–15.3 ± 0.6	+10.0 ± 1.2
Winkle *(Littorina littorea)*	16	Whole muscle	–16.0 ± 0.6	+9.7 ± 1.4

Outliers in the age data were initially excluded using a χ^2 test; an overall ΔR was then calculated using the multiple paired marine/terrestrial sample approach, whereby a ΔR value was calculated for all possible pairs and then a weighted mean paired offset was calculated for the context, with

Table 5 Faunal carbon isotope tissue offset values. Mean values ±1σ.

Species	Nr sample pairs	$\Delta^{13}C_{\text{muscle protein-bone collagen + lipids}}$	$\Delta^{13}C_{\text{muscle protein-bone collagen}}$	$\Delta^{13}C_{\text{bone collagen-collagen + lipids}}$
Cattle *(Bos Taurus)*	3	–2.0 ± 0.1	–1.7 ± 0.1	–0.3 ± 0.2
Sheep *(Ovis aries)*	6	–2.2 ± 0.2	–2.2 ± 0.6	–0.1 ± 0.6
Red deer *(Cervus elaphus)*	10	–1.7 ± 0.3	–1.6 ± 0.4	–0.1 ± 0.4
Roe deer *(Capreolus capreolus)*	9	–2.4 ± 0.8	–2.3 ± 0.2	–0.2 ± 0.7
TERRESTRIAL	**28**	**–2.1 ± 0.6**	**–1.9 ± 0.5**	**–0.2 ± 0.5**
Cod *(Gadus morhua)*	10	–0.4 ± 0.8	–2.6 ± 0.5	+ 2.2 ± 0.7
Pollock (*Pollachius pollachius*)	10	–2.0 ± 0.2	–2.7 ± 0.4	+ 0.7 ± 0.3
Haddock *(Melanogrammus aeglefinus)*	10	–2.8 ± 0.3	–2.7 ± 0.3	–0.1 ± 0.4
MARINE	**30**	**–1.7 ± 1.1**	**–2.7 ± 0.4**	**+ 0.9 ± 1.1**

the variability expressed as the standard error for predicted values (Cook et al. 2015). The human dietary calculations and the new ΔR values were then to be used to recalibrate the existing ^{14}C measurements of the human samples using OxCal 4.2, to assess whether any marine consumption detected would have a significant effect on the ages of the human bone collagen.

Published stable isotope values for four human individuals from Carding Mill Bay (Schulting and Richards 2002) were modeled in FRUITS along with the new baseline measurements to create dietary reconstructions. Food values for FRUITS models were calculated using species specific and local $\Delta^{13}C_{\text{muscle protein-bone collagen}}$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}}$ offsets. These offsets were derived by measuring the $\delta^{13}C$ and $\delta^{15}N$ values of paired flesh-bone collagen samples from representative modern marine and terrestrial species and calculating the difference between flesh and bone values. The mean values of these offsets were used to convert the faunal bone collagen baseline values to food values (see Tables 5 and 6).

RESULTS

Quality Assurance

Quality indicators were applied to the isotope measurements after pretreatment and after measurement to ensure that the data were reliable. For ancient bone collagen samples, collagen recovery must be greater than 1% of the total sample weight and the C/N atomic ratio value must be within the range 2.9–3.6 (DeNiro, 1985). Three samples (GU18879, GU18880, and GU18881) were outside of the recommended atomic ratio range and were excluded from further discussion. Quality control indicators for sulphur isotope values for mammal bone collagen are C:S atomic ratio = 600 ± 300 and N:S atomic ratio = 200 ± 100, while for fish

Table 6 Faunal nitrogen isotope tissue offset values. Mean values ±1σ.

Species	Nr sample pairs	$\Delta^{15}N_{muscle\ protein\text{-}bone\ collagen+lipids}$	$\Delta^{15}N_{muscle\ protein\text{-}bone\ collagen}$	$\Delta^{15}N_{bone\ collagen\text{-}collagen\ inc.\ lipids}$
Cattle *(Bos Taurus)*	3	–0.8 ± 0.5	–0.9 ± 0.2	+0.2 ± 0.7
Sheep *(Ovis aries)*	6	+0.1 ± 0.9	+0.4 ± 1.0	–0.3 ± 0.8
Red deer *(Cervus elaphus)*	10	+0.1 ± 0.6	+0.3 ± 0.7	–0.2 ± 0.2
Roe deer *(Capreolus capreolus)*	9	+0.6 ± 1.0	+0.5 ± 0.5	+0.1 ± 0.8
TERRESTRIAL	**28**	**+0.2 ± 0.9**	**+0.3 ± 0.8**	**–0.1 ± 0.7**
Cod *(Gadus morhua)*	10	+0.5 ± 0.3	+0.5 ± 0.2	–0.0 ± 0.4
Pollock *(Pollachius pollachius)*	10	+0.3 ± 0.4	+0.2 ± 0.5	+0.1 ± 0.2
Haddock *(Melanogrammus aeglefinus)*	10	+0.3 ± 0.4	+0.3 ± 0.5	–0.0 ± 0.2
MARINE	**30**	**+0.4 ± 0.4**	**+0.4 ± 0.4**	**–0.0 ± 0.2**

bone collagen they are C:S atomic ratio = 175 ± 50 and N:S atomic ratio = 60 ± 20 (Nehlich and Richards 2009). Four samples (GU18879, GU18888, GU18890, GU18893) were outside of these and excluded from further consideration. There are currently no accepted quality indicators for modern flesh or bone collagen including lipid samples measured by CF-IRMS, however we can be confident that the samples were not degraded since they were stored at –20° C before pretreatment and they never came into contact with a burial environment.

Ancient Bone Collagen

Table 1 illustrates stable carbon, nitrogen and sulphur isotope measurements for herbivore bone collagen from Carding Mill Bay and marine fish from Robert's Haven and Quoygrew. For herbivores, the mean isotope values were: $\delta^{13}C = -22.8 \pm 0.43‰$, $\delta^{15}N = +3.1 \pm 0.47‰$ and $\delta^{34}S = +20.0 \pm 0.65‰$. For marine fish, the values were: $\delta^{13}C = -13.5 \pm 0.66‰$, $\delta^{15}N = +14.1 \pm 0.69‰$ and $\delta^{34}S = +16.5 \pm 0.44‰$. The $\delta^{13}C$ and $\delta^{15}N$ results are typical of terrestrial herbivores that have been raised on unfertilized land (Bogaard et al. 2013), and wild marine fish (Schoeninger and DeNiro 1984). However, the sulphur isotope measurements made on the herbivores are indicative of a sea-spray effect, whereby marine sulphur is directly ingested by animals that graze near the sea (Wadleigh et al. 1994). For this reason, the sulphur isotope measurements were not used in the FRUITS models to reconstruct human paleodiet.

Modern Terrestrial Isotope Measurements

Table 2 illustrates average stable carbon and nitrogen isotope measurements for modern terrestrial herbivores that were candidates to supplement the faunal baseline at Carding Mill Bay. These values were used to produce geographically relevant food values for the FRUITS models. The mean isotope values for different tissue fractions were $\delta^{13}C = -24.9 \pm 0.61‰$ and $\delta^{15}N = +5.2 \pm 1.74‰$ for bone collagen, $\delta^{13}C = -24.8 \pm 0.71‰$ and

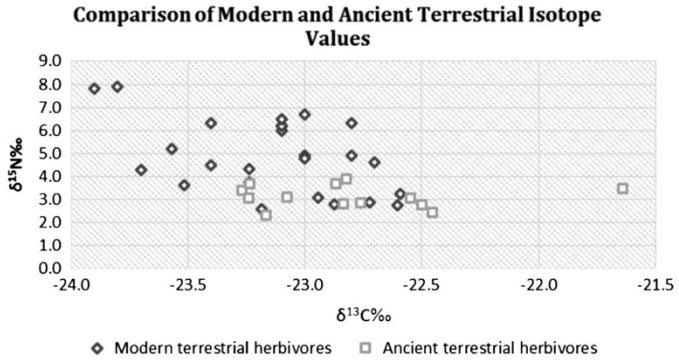

Figure 2 Carbon and nitrogen stable isotope measurements of modern and ancient terrestrial herbivore bone collagen. Modern values corrected for the Suess effect.

$\delta^{15}N = +5.2 \pm 1.79‰$ for bone collagen including lipids, and $\delta^{13}C = -26.8 \pm 0.71‰$ and $\delta^{15}N = +5.4 \pm 1.70‰$ for muscle protein.

To account for the atmospheric Suess effect in modern organic samples, whereby organisms are depleted in ^{13}C compared to ancient samples as a result of the release of carbon from fossil fuels in the last two centuries, carbon isotope data must be adjusted by +1.5‰ (Beavan Athfield et al. 2008). Comparing the adjusted modern bone collagen isotope measurements with the measurements from ancient animals at Carding Mill Bay demonstrated that modern and ancient populations are not isotopically comparable (see Figure 2). In addition, there is a large range in the stable nitrogen isotope values of modern herbivore bone collagen ($1\sigma = 1.70$); this implies large physiological or dietary variations within the modern population that are not present in the ancient population. For this reason, the measurements of modern terrestrial bone collagen were excluded from the FRUITS models as they were deemed incomparable with ancient terrestrial fauna.

Modern Marine Isotope Measurements

Table 3 summarizes average stable carbon, nitrogen, and sulphur isotope measurements for modern marine fish species, which were candidates to supplement the marine faunal baseline. The mean isotope values for different tissue fractions were: $\delta^{13}C = -15.2 \pm 0.77‰$ and $\delta^{15}N = +11.8 \pm 1.66‰$ for bone collagen, $\delta^{13}C = -16.1 \pm 1.41‰$ and $\delta^{15}N = +11.8 \pm 1.72‰$ for bone collagen including lipids, and $\delta^{13}C = -17.9 \pm 0.71‰$ and $\delta^{15}N = +12.1 \pm 1.82‰$ for muscle protein.

In contrast to the terrestrial fauna, modern marine fish bone collagen appears to be a good analog for ancient marine bone collagen. Figure 3 shows carbon and nitrogen isotope measurements for modern and ancient cod bone collagen, and modern shellfish protein. The modern data has been corrected to account for the marine Suess effect. There is significant overlap in the isotope data of modern and archaeological cod bone collagen, indicating that chronologically distinct marine populations are isotopically comparable. Since modern and ancient cod bone collagen are comparable, we have made the assumption that modern shellfish flesh samples are also suitable analogs. Isotope data from these samples were used alongside the ancient measurements in FRUITS to build a representative marine dietary isotope baseline.

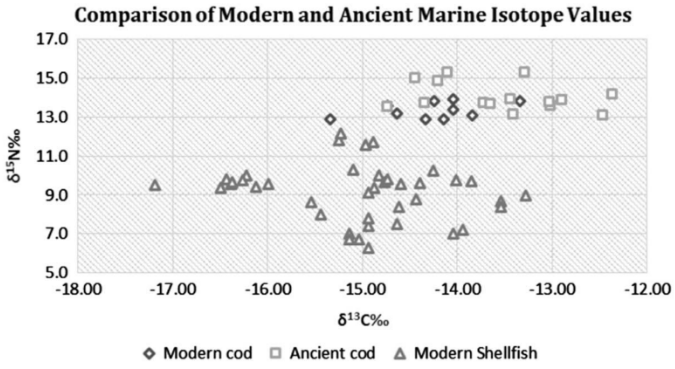

Figure 3 Carbon and nitrogen stable isotope measurements of modern and ancient cod bone collagen, and modern shellfish protein. Modern values corrected for the Suess effect.

Isotopic Tissue Offsets

While modern terrestrial fauna proved to be unsuitable analogs for ancient samples for the reasons discussed above, stable isotope data from modern animals were useful when calculating tissue offsets that are necessary for modeling diet in FRUITS. Differences in $\delta^{13}C$ between muscle tissue and bone collagen are related to physiological differences in the tissue structure: lipids are relatively depleted in ^{13}C relative to bone collagen and flesh, and flesh is relatively depleted in ^{13}C compared to bone collagen (Pinnegar and Polunin 1999; Fernandes et al. 2015). These offset values may differ between species, so it is important to use appropriate offsets when reconstructing diet using FRUITS. Isotopic differences between muscle protein and bone collagen in both modern terrestrial samples (Table 2) and modern marine samples (Table 3) were therefore used to produce the $\Delta^{13}C_{\text{muscle protein-bone collagen}}$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}}$ values shown in Tables 5 and 6.

Human Dietary Reconstruction Using FRUITS

Tables 6, 8, and 9 summarize dietary and ^{14}C data for four human bones (Table 7) recovered from different contexts of the Carding Mill Bay midden. The stable isotope data in Table 8 were used to model dietary intake using FRUITS. To establish whether there was a significant marine reservoir effect in the human bone collagen, the ^{14}C ages given in Table 7 were recalibrated using the marine food source estimates generated by FRUITS and the new ΔR value that was obtained (see Tables 8–13).

The modeling parameters considered when reconstructing diet at Carding Mill Bay for each of the human samples were as follows: the protein dietary intake was via the routed model, with carbon and nitrogen isotope values from four consumer bone collagen samples specified with an error of 0.5‰ to account for intra-individual variability, following (Fernandes et al. 2015). Tissue offsets applied to obtain the food values were as follows: terrestrial herbivore $\Delta^{13}C_{\text{muscle protein-bone collagen}} = -1.9$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}} = +0.3$, marine fish $\Delta^{13}C_{\text{muscle protein-bone collagen}} = -2.7$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}} = +0.4$. No tissue offsets were required for shellfish muscle protein values used. One dietary fraction (protein) from each of three food groups (terrestrial herbivores, marine fish, and marine shellfish) was then defined

Table 7 ^{14}C ages and paleodietary isotope measurements of human bone collagen from Carding Mill Bay (Schulting and Richards 2002).

Sample ID	Context nr	^{14}C age (BP)	$\delta^{13}C_{VPBD}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	C/N molar
OxA-7890	XXIII	4330 ± 60	–21.4	9.8	3.1
OxA-7665	VII	4690 ± 40	–21.5	9.6	3.2
OxA-7664	XV	4830 ± 45	–21.0	8.9	3.1
OxA-7663	XIV	4800 ± 50	–21.5	9.0	3.2

Table 8 ^{14}C and $\delta^{13}C$ measurements of marine shell and terrestrial herbivore bone collagen for ΔR determination.

Context nr	Sample ID	Sample type	^{14}C age (yr BP ± 1σ)	$\delta^{13}C$ (‰ VPDB)
XIV	GU39625	Terrestrial	5273 ± 39	–23.3
XIV	GU39626	Terrestrial	5190 ± 36	–23.2
XIV	GU39627	Terrestrial	5040 ± 37	–23.3
XIV	GU39628	Terrestrial	4848 ± 38	–23.4
XIV	GU39633	Marine	5413 ± 28	0.6
XIV	GU39634	Marine	5522 ± 28	–0.2
XIV	GU39635	Marine	5424 ± 29	0.2
XIV	GU39636	Marine	5395 ± 28	0.8
XV	GU39629	Terrestrial	5334 ± 39	–22.6
XV	GU39630	Terrestrial	5320 ± 39	–23.3
XV	GU39631	Terrestrial	5155 ± 39	–23.4
XV	GU39632	Terrestrial	5278 ± 36	–22.2
XV	GU39637	Marine	5519 ± 28	0.6
XV	GU39638	Marine	5467 ± 29	0.4
XV	GU39639	Marine	5575 ± 29	0.9
XV	GU39640	Marine	5573 ± 28	0.1

Table 9 Results of χ^2 tests on all ^{14}C ages for terrestrial and marine samples from contexts XIV and XV.

Context nr	Terrestrial χ^2 T value	Marine χ^2 T value
XIV	72.10 ($\chi^2_{:0.05} = 7.81$)	12.39 ($\chi^2_{:0.05} = 7.81$)
XV	13.07 ($\chi^2_{:0.05} = 7.81$)	9.56 ($\chi^2_{:0.05} = 7.81$)

using the average stable isotope values and standard error of the mean of the modern faunal muscle protein: $\delta^{13}C_{herbivores} = -24.7 \pm 0.1‰$ and $\delta^{15}N_{herbivores} = +3.4 \pm 0.1‰$, $\delta^{13}C_{fish} = -16.8 \pm 0.1‰$ and $\delta^{15}N_{fish} = +12.9 \pm 0.3‰$, and $\delta^{13}C_{shellfish} = -15.2 \pm 0.1‰$ and $\delta^{15}N_{shellfish} = +9.5 \pm 0.2‰$. These values have been corrected to account for the marine Suess effect: modern marine carbon isotope data must be adjusted by 0.86‰ (Beavan Athfield et al. 2008). Chosen diet to collagen offsets were 1 ± 1‰ for $\delta^{13}C$ and 5.5 ± 0.5‰ for $\delta^{15}N$. Table 12 and Figure 4 illustrate the results of dietary reconstruction using FRUITS.

Table 10 Data for contexts XIV and XV that contained inconsistent measurements on the basis of χ^2 tests.*

Context nr	Consistent measurements	Age BP ± 1σ	Inconsistent measurements	Age BP ± 1σ	T value
XIV (terrestrial)	No consistent terrestrial measurements were identified; therefore, a judgement call was made to include all measurements when calculating the ΔR value.		GU39625	5273 ± 39	72.10
			GU39626	5190 ± 36	
			GU39627	5040 ± 37	
			GU39628	4848 ± 38	
XIV (marine)	GU39633	5413 ± 28	GU39634	5522 ± 28	3.55
	GU39635	5424 ± 29			
	GU39636	5935 ± 28			
XV (terrestrial)	GU39629	5334 ± 39	GU39631	5155 ± 39	1.23
	GU39630	5320 ± 39			
	GU39632	5278 ± 36			
XV (marine)	GU39637	5519 ± 28	GU39638	5467 ± 29	2.54
	GU39639	5575 ± 29			
	GU39640	5573 ± 28			

*Consistent measurements were used to calculate values of ΔR. T-statistics shown are for consistent groups.

Table 11 ΔR values for Carding Mill Bay from literature sources and this study.

Context nr	ΔR Value	Source
XIII	+150 ± 28	Ascough et al. (2007)
XIV	–44 ± 91	Reimer et al. (2002)
XIV	–130 ± 34	This research
XV	+86 ±67	Reimer et al. (2002)

Table 12 Summary data for human diet at Carding Mill Bay derived from FRUITS.

Sample ID	Marine fish contribution (%)	Marine shellfish contribution (%)	Terrestrial herbivore contribution (%)
OxA-7890	8 ± 6	13 ± 8	79 ± 7
OxA-7665	7 ± 5	12 ± 8	81 ± 7
OxA-7664	6 ± 5	10 ± 7	84 ± 6
OxA-7663	5 ± 4	10 ± 7	85 ± 6

Recalibrating Radiocarbon Dates at Carding Mill Bay

ΔR values were calculated for contexts XIV and XV at the site. For context XIV marine samples, one sample (GU39634) was excluded as an outlier and the remaining three samples passed the χ^2 test. However, the terrestrial samples failed the χ^2 test completely, with no two samples passing. On that basis, we determined that context XIV is mixed and unsuitable for deriving a ΔR value. For context XV, one marine and one terrestrial sample (GU39638 and GU39631, respectively) were removed and the remaining three samples in both groups passed

Table 13 Summary of recalibrated ^{14}C dates of humans from Carding Mill Bay. Reported with 95% confidence interval.

Sample ID	Previous age range (cal BC)	Recalibrated age range (cal BC)
OxA-7890	3096–2878	3089–2680
OxA-7665	3632–3366	3625–3333
OxA-7664	3698–3524	3661–3379
OxA-7663	3660–3384	3646–3376

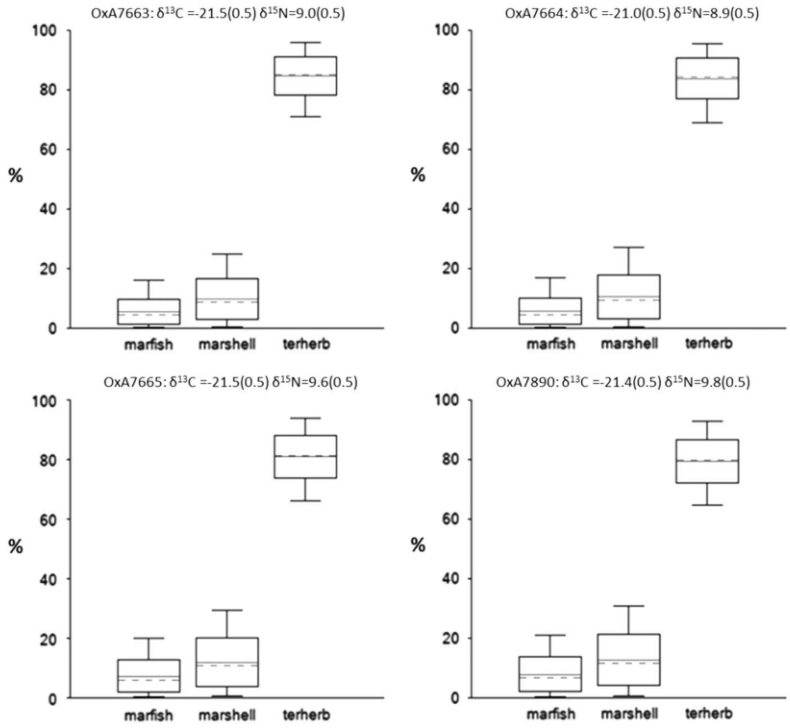

Figure 4 FRUITS reconstructions of human diet at Carding Mill Bay. Boxes represent a 68% credible interval and whiskers represent a 95% credible interval. Within the boxes, the solid line represents the estimated median and the dashed line represents the estimated mean.

the χ^2 test. In this case, context XV was deemed suitable for ΔR calculation. The calculated value was –130 ± 34 ^{14}C yr.

The ^{14}C ages for the four humans at Carding Mill Bay were first calibrated using the terrestrial calibration curve within OxCal 4.2, to provide baseline ^{14}C dates (Reimer et al. 2013). The ages were then recalibrated using the mixed marine/terrestrial calibration curve within OxCal 4.2 (Reimer et al. 2002), employing the marine dietary information for each individual obtained from FRUITS, together with the recalculated ΔR value. See Figure 5 for all ^{14}C calibrations for this site.

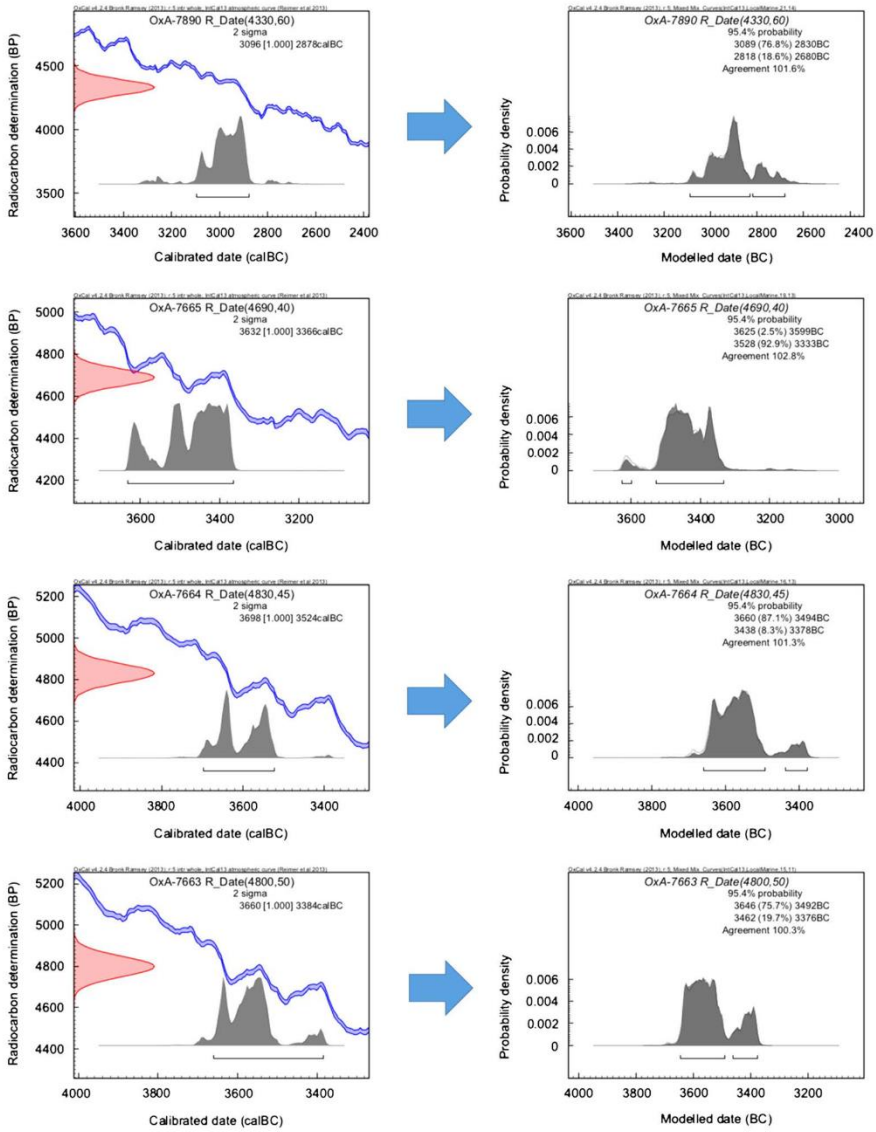

Figure 5 Recalibrated radiocarbon dates of humans from Carding Mill Bay using an updated ΔR value of −130 ± 34 ^{14}C yr and percentage marine contribution to diet calculated using FRUITS.

DISCUSSION

There are three strands of the investigation that require discussion: the dietary habits and dates of the human remains at Carding Mill Bay, the subsistence strategies of the population, and the novel use of FRUITS to model Neolithic diet in western Scotland.

First, and most significantly, the results of the FRUITS reconstruction of all four humans reveal modest amounts (15 ± 11 to 21 ± 14%) of marine resources in the diet. This is significant, given that the site and the human samples are dated to the Neolithic, when exploitation of marine foods had supposedly been abandoned in favor of farming (Richards et al. 2003). Our results are in contrast to previous interpretations of bulk bone isotope data that suggested a complete absence of marine resources in the Neolithic diet (Richards et al. 2003; Richards and Schulting 2006; Cramp et al. 2014), but are in agreement with the archaeological record for the site.

In all human samples analyzed, we see a diet dominated by terrestrial resources, but supplemented with marine fish and shellfish. The models suggest that shellfish were a more important resource at Carding Mill Bay than marine fish, and this is reflected in the archaeological record, with shellfish being far more abundant than fish remains (Connock et al. 1991). It seems likely that the use of marine resources at this time would have been secondary to farm produce, either as a supplement to the diet or as a famine food in times of crop/livestock failure. The employment of shellfish gathering being prioritized over fishing is sensible: shellfish were easy to source with very little skill, and required no tools more complicated than a rock to dislodge them. Fishing, on the other hand, required specialist skill and equipment, took more time, and quite probably yielded fewer rewards. If Early Neolithic communities exploited wild marine resources, it is sensible that they would choose the simpler and more rewarding over the difficult and time consuming.

The findings at Carding Mill Bay have parallels with results derived from high-resolution measurements of stable isotopes in tooth dentine from Neolithic individuals in Shetland (Montgomery et al. 2013). These showed that at least during their childhood years they periodically and temporarily returned to eating marine resources before reverting back to a more terrestrial-based diet. The authors hypothesized that this was in response to difficulties encountered while attempting to maintain a sedentary farming culture in a marginal environment (Montgomery et al. 2013). While our bulk bone collagen isotope values cannot reveal periodic returns to marine resources at different stages in life, they do show small inputs of marine resources to the diet, which is also evident in the results from Shetland.

Following our recalibration of the four ^{14}C ages derived from human bone collagen, to take into account the improved ΔR value for the site and the potential marine reservoir effect caused by the consumption of shellfish and fish, we find very little shift in the ages. While Figure 5 and Table 13 show that the recalibrated ages are less precise, our assertion is that they are more accurate. This is noteworthy, since, even after correction of the ages, these individuals date to the first half of the Scottish Neolithic; not only do we demonstrate that the chronology of the site is reliable and secure, but we show that fish and shellfish in the diet can be firmly associated with the Neolithic.

Further information about subsistence practices at Carding Mill Bay can be derived from the stable isotope data of the Neolithic terrestrial herbivores. The sulphur isotope measurements of all herbivores at the site indicate a marine signal, demonstrating the ingestion of sulphur indirectly from seawater, most commonly described as the "sea-spray effect" (Wadleigh et al. 1994). This effect, caused by animals grazing close to a coastline, as observed here, suggests that the animals were probably raised locally and not moved from inland sites to the Oban area. The low $\delta^{15}N$ values for the herbivore bone collagen also suggest that the land on which these animals grazed was not fertilized with manure, and the low $\delta^{13}C$ values indicate they were not foddered with seaweed (Bogaard et al. 2013). While we can be confident of the latter point

because significant foddering would result in a slight "marine signature" to the $\delta^{13}C$ values, we cannot say the same of the former since comparison of nitrogen isotope values from pre-Neolithic herbivores would be required to be sure that the low values are not simply as a result of a natural geographical variation in isotopes.

We can also make some observations about FRUITS as a dietary reconstruction model. The accuracy and reliability of FRUITS has been demonstrated in several past studies (Fernandes et al. 2014, 2015; Sayle et al. 2016), however, the application of modeling parameters has always been at the user's discretion. $\Delta^{13}C_{\text{muscle protein-bone collagen}}$ and $\Delta^{15}N_{\text{muscle protein-bone collagen}}$ offset values used here have been specifically calculated from tissue fractions of animals of the same species as those analyzed in the isotope faunal baseline. Offsets are reasonably comparable across species from the same environment and the error associated with each value indicates that they are relatively accurate representations of tissue offsets (see Tables 4 and 5). The use of empirically derived offsets in FRUITS removes any uncertainty associated with values calculated from unrepresentative species and geographically incomparable sites, thus strengthening the reliability of the models in this study.

Finally, we have demonstrated the ability of FRUITS to distinguish between the consumption of different food groups from the same environment. Traditional interpretations of stable carbon and nitrogen isotope plots are unable to identify the consumption of shellfish separately from the consumption of fish. Indeed, dietary interpretations based on a standard linear mixing model never even consider shellfish as a potential food source since they cannot be included in a bone collagen faunal baseline. The abundance of shellfish remains in coastal middens in Scotland necessitates their consideration as a part of the Neolithic diet. The fact that the isotopic food value of shellfish differs in $\delta^{15}N$ enrichment from fish suggests they should be treated as a distinct food source in future dietary studies.

CONCLUSIONS

At Carding Mill Bay, we demonstrate how the use of stable isotope measurements from human and animal bone collagen, realistic collagen/muscle isotope offsets, and the Bayesian mixing model (FRUITS) for determining paleodiet reveals the presence of small amounts of marine resources in the diet of Early Neolithic humans recovered from this site. Our consideration of archaeological and stable isotope evidence from Neolithic western Scotland suggests that the dietary shifts from marine to terrestrial resources were not as rapid or absolute as has been suggested. Finally, we can make certain suggestions about farming practices at this coastal site, with evidence showing that animals at Carding Mill Bay may have been of local origin and that foddering and fertilization practices, observed in later Neolithic sites, were not present.

Our results have implications both for dietary research using stable isotopes and for archaeological investigations of shell middens. When building a picture of ancient diet using stable isotopes, it is important to consider all available dietary evidence from the site and include this in a dietary baseline. The importance of using dietary baselines is well established, but we must ensure that they are also representative of the diet consumed by the human individuals analyzed. Where there is evidence of dietary habits, but a lack of samples suitable for stable isotope analysis, appropriate modern analogs should be used to increase sample size. We must also consider the appropriate model to use when estimating ancient diets. In sites like Carding Mill Bay, with evidence of varying subsistence practices, it is essential to use a Bayesian mixing model such as FRUITS, which is capable of discerning small contributions of different food groups.

ACKNOWLEDGMENTS

The authors thank the staff of the SUERC radiocarbon and AMS laboratories for assistance with sample pretreatment, stable isotope, and ^{14}C measurements. We also thank Ricardo Fernandes for the time spent providing training and advising on the appropriate use of FRUITS. The assistance of Sheena Fraser with archaeozoological analysis of faunal samples is gratefully acknowledged. We thank two anonymous reviewers for their comments on this paper. Samples for analysis were obtained in collaboration with staff of the Glasgow Museums Research Centre and Historic Environment Scotland. Funding for this research was provided by the AHRC (Grant no. AH/L008521/1).

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