Stable isotope evidence for diet change in Roman and Medieval Italy: local, regional and continental perspectives

Erika Nitsch
Linacre College
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Submitted in partial completion of the
Doctor of Philosophy

Hilary Term, 2012

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Abstract

This thesis investigated dietary change in Roman and Medieval Europe c. AD 1-1500 using stable isotope analysis of humans and animals. Historical and archaeological data present two possibilities for how the social, political and economic changes of this period may have affected food practices. One argument suggests the population collapse and economic depression of the Early Medieval period increased the availability and consumption of meat. The counter-argument suggests that agricultural and economic patterns were constrained by local circumstances, and that no significant dietary change occurred.

This study combined local-scale isotopic analysis from central Italy with a meta-analysis of all available previously published data from Europe c. AD 1-1500. Mixed multi-level models were used to control for random inter-site variation, and to investigate the effect of multiple factors (Phase, Location, proximity to coast, Age, Sex, Species) on δ^{13}C and δ^{15}N. Within central Italy, 430 humans and 29 animals were analysed from eight archaeological sites dating from the 5th century BC to the 15th century AD. There were no significant differences through time, but coastal sites had significantly higher δ^{13}C and urban sites had significantly higher δ^{15}N. Across Europe, Early Medieval humans (c. AD 500-1000) had slightly but significantly lower δ^{13}C and δ^{15}N compared to Roman and Late Medieval individuals. This was the opposite of the effect expected due to increasing meat consumption at this time.

A number of complicating factors were discussed, including the effect of climate change, changing agricultural practices and uncertainty in estimating animal protein consumption based on δ^{13}C and δ^{15}N. When these effects are considered, the isotopic changes observed through time do not eliminate the possibility of increased meat consumption in the Early Medieval period. Nevertheless, the data presented from Roman Italy, and new models for estimating animal protein consumption, indicate that Roman historical sources may underestimate the dietary role of animal protein, and that therefore Roman and Early Medieval food production and consumption patterns were similar.

Acknowledgements

I would like to thank my supervisor Prof Robert Hedges for his years of support, advice and criticism, and for ensuring that I left our meetings with more questions than answers. I am extremely grateful to Dr Peter Ditchfield for technical support at the RLAHA. I would also like to thank the members of the Biomolecular Archaeology research group at the RLAHA for providing feedback throughout this project, especially Prof Julia Lee-Thorp, Dr Rick Schulting, and Dr James McCullagh. In addition laboratory advice, Julia Hamilton also provided species identification for the faunal samples analysed in this study. Trine Nielsen volunteered as a research assistant in the summer of 2010 and undertook collagen extraction of several of the samples. Dr Lunn from the Department of Statistics (Oxford) provided consultation for the statistical models used in this study, although I claim ownership of any errors in the application of his advice. I owe a great deal to Anne Leask for such professional proofreading, and for wanting the final product to be better than I imagined it could be.

This project would not have been possible without Dr Elizabeth Fentress and Dr Caroline Goodson, who not only provided access to the excavations at Villamagna, but also facilitated much of the sampling I was able to undertake in Italy. Anthropological information for the Villamagna skeletons was provided by Dr Francesca Candilio, Samantha Cox, and Rowan Brixley. I am very grateful to Dr Mauro Rubini at the Soprintendenza per i Beni Archeologici del Lazio for providing additional samples, and to Samantha Cox for assisting me in collecting them.

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We must eat. If, in the face of that dread fact, we can find other nourishment, and tolerance and compassion for it, we'll be no less full of human dignity. There is communion of more than our bodies when bread is broken and wine drunk. And that is my answer, when people ask me: Why do you write about hunger, and not wars or love?

—M. F. K. Fisher, *The Gastronomical Me*

1

Introduction

This thesis explores changing food habits in Europe and the Mediterranean, focused on central Italy, during the Roman empire and the thousand years that followed its collapse. This period (AD 1 to 1500) saw a number of transformations: the end of classical antiquity, the economic contraction and population movements of the early Middle Ages, and the renewed growth and urbanization of the high Middle Ages that prefigured the economic and political landscape of modern Europe. Previous studies of these transitions have focused on economic and cultural changes as viewed through material culture and texts. This thesis is an answer to more specific calls to examine the dietary implications of the Roman to Medieval economic transition (Arthur, 2004; Christie, 2006; Hodges, 1997; McCormick, 2001).

Evidence for changing patterns of consumption comes from textual, iconographic and archaeological sources, but specific information about food practices is rare, especially for the non-elite (see Chapter 2). The specifics of ancient diets have been obtained in the last few years through the increasing number of skeletally-based dietary reconstruction techniques, including tooth-wear analysis, trace element analysis, and stable isotope analysis. Stable isotope analysis provides a direct and quantifiable reconstruction of the intake of certain food categories, and so offers the opportunity to explore otherwise invisible dietary trends. This technique is not without its cautions, caveats and assumptions, but can be used in conjunction with other forms of evidence to form a more complete picture of ancient diet (see Chapter 3).

This study performed stable isotope analysis on several hundred individuals from Roman and Medieval cemeteries in central Italy to reconstruct local-scale dietary changes through time (see Chapters 4 and 5), responding to the need for a locally-focused perspective on food, economy, environment and agricultural in this period (Hodges, 1982). The wider context of these Italian trends was then reconstructed using a meta-analysis of previously published isotopic dietary studies from Europe and the Mediterranean in the Roman and Medieval periods (see Chapter 6).

This chapter provides a review of the theoretical framework of nutritional anthropology, which identifies the economic and social patterns which shape, and are shaped by, food practices. It then gives an introduction to the historical, social and economic context of this study. The anthropological framework is applied to the historical trends in order to identify the themes of social and economic change in Italy following the end of the Roman empire. These are used to make predictions about how dietary patterns—as observed in stable isotope ratios—may have been affected. This chapter concludes with an outline of the research design and hypotheses.

1.1 Why do people eat what they eat? The Anthropology of Food

Why study food? Food is of interest to archaeologists, anthropologists and historians for two reasons. The first is because of its relationship with economics and trade. The second is because of food's function as a signifier of social meaning. All animals require carbohydrates and lipids for energy, and protein for the synthesis and maintenance of tissues. Humans are omnivores, and have a large variety of foods they can eat to satisfy their needs. Taste and flavour guide our eating habits partly because of these physiological needs. The foods that are most able to satisfy our physiological needs (fatty, sweet, meaty foods) also taste the best (Yudkin, 1978).

Beyond basic nutrition, the cultural and economic limitations imposed on food choices are of great interest to anthropologists. Nineteenth-century anthropologists focused on the symbolic and religious aspects of food: on taboo, totemism, sacrifice and communion. Through French sociology came the influence of functionalism, exemplified by the work of Alfred Radcliffe-Brown on the socializing role of food in the Andaman islands (Radcliffe-Brown, 1922), and Audrey Richard's work in the 1930s on the function of food in forming human relationships among the southern Bantu (Richards, 1932).

Structuralism sought to gather meaning from food systems by describing the underlying system of thought. Lévi-Strauss noted that cooking, along with language, is a trait particular to humans. He described a 'culinary triangle' to distinguish between three aspects of cuisine: the raw, the cooked and the rotten (Lévi-Strauss, 1970). Lévi-Strauss's work emphasized the importance of understanding the entire culinary structure, which could be used to interpret cross-cultural food behaviours. Barthes applied a structuralist approach to food to explain how food always functions as a system of communication (Barthes, 1975). He sought a 'grammar of foods' to determine what different foods, techniques and habits signify in different contexts. He noted that the manner of preparation is important to the cultural meaning, and that the food item itself is rarely the signifier of meaning, except in the case of some items of food that are valued for their cost alone, such as caviar. The term 'foodways' can be used to refer to these collective ideas, to the 'modes of feeling, thinking and behaving about food that are common to a cultural group' (Simoons, 1961, 3).

The role of food as the economic basis of society has also been a focus of anthropological study. This originated with the classification of societies on the basis of their food procurement strategies and the social evolution theories of Lewis Henry Morgan, published in his *Ancient Society* in 1877. The link between certain food behaviours and certain cultural traits suggested that food had an effect on social and economic organization. This idea continued to be developed in the 20th century. The term 'adaptive strategy' has been used to describe a group's means of maximizing their energy intake (Cohen, 1974). Societies were found to share many cultural features, depending on the adaptive strategy (hunting-gathering, horticulture/agriculture, pastoralism and industrialization) they employed. In this way, the economic model of food behaviours could be used to predict and explain social characteristics.

Economic limitations affect the availability of foods and can include both ecological and geographic constraints, as well as the availability created by trade, markets and differential access to wealth. Economic and social influences on food choices are never mutually exclusive, and are united in the role that food plays in acquiring and displaying status, and especially through the conspicuous consumption of certain food items (Bourdieu, 1984). The foods that are desirable for eating are usually those rich in fat and other nutrients and a higher status is usually given to those who can produce, consume or distribute those foods (Wissener, 1996). The method of preparing the food, or the 'cuisine' can also be used to achieve status (Goody, 1982). The giving of food, especially as a public feast, confers status on the giver, who accumulates what Bourdieu (1984) called 'symbolic capital'.

The most relevant contribution to the study of food in archaeology was the emphasis that Goody (1982) placed on the historical factors that influence food behaviour. He pointed out that despite the fact that food behaviour is extremely conservative, large culinary changes have taken place in Europe in the last 400 years, citing the role of the potato in Irish cuisine and the role of the tomato in Italian cuisine as examples. Goody sought to understand how and why elite patterns of consumption became differentiated from those of the non-elite in Europe and Asia, with the creation of what he calls 'cuisine', while the food of African cultures remained largely undifferentiated in style between various status levels. The important features that Goody identifies in Eurasia that created this elite cuisine are the technologies for intensive agriculture (manuring, ploughing, irrigation) that created surplus and variety, and the literacy that provided the means for writing and communicating ideas about food. Some of the earliest writings on cuisine come from Greece and Rome, and are discussed in Chapter 2.

Dietler (1996) demonstrated the way in which Goody's ideas of cuisine could be seen in material culture in an archaeological context. In Early Iron Age Western Europe he noted a difference in the import of Etruscan pottery between the southern coast of France, where wine amphorae were predominantly present, and the Halstatt region of central Europe where fine drinking objects were present. He attributed this pattern to a difference in the type of feasting in each area. The importance of the ingredients themselves in France (the wine) indicated the use of feasting as an economic transaction, while the emphasis on specialized drinking wear in Halstatt was attributed to the need for status recognition.

Geography and technology are two of the economic factors limiting food choice in most societies. By highlighting the conservatism of food culture, Goody creates the need to assess the historical development of the entire food system, including the interplay between foodways and geographic or technological constraints. At the same time, 'calorific determinism' (Horden and Purcell, 2000, 175), defining food systems based on difficult to measure ecological variables, should be avoided. Economic, ecological and geographic constraints exist, but cultural beliefs are still a driving force. As Duby (1974, 29) wrote, a society 'endeavours to overcome the limitations of soil and climate in order to procure at all costs foodstuffs that its customs and rites ordain'.

The interpretive framework I use for this study reflects the nature of the data. Stable isotope analysis of human bone provides semi-quantitative information about broad dietary categories. It is not sensitive to small amounts of food (such as valuable spices) nor to the differences between similar food categories (such as the difference between consuming pork or any other animal meat).[1] It is also unable to detect different methods of preparation. All of these may have been important cultural factors. Nevertheless, unlike other ways of reconstructing ancient diet, it provides resolution at the level of individual dietary choices, averaged over the last several years of life. Gumerman (1997) argues that one of the features of complex societies is that food choices are determined by personal and cultural choices, as well as economic constraints. Stable isotope analysis can be used at an individual level to understand the social parameters of food choices, and on a population-level to observe long-term economic trends of food availability. Reflecting both sides of the anthropological tradition discussed above, this study will reconstruct diet both in terms of 'foodways' (social meaning) and 'adaptive strategies' (economic role).

1.2 Historical context

The historical scope of this research stretches from the height of imperial Roman power in the first century AD to the end of the Middle Ages and beginning of the Renaissance in the 15th and 16th century. Throughout this work, I have maintained the tripartite chronological divisions followed by many historians (Le Goff, 2007; Winks and Ruiz, 2005), between the 'Roman' (up to AD 500) 'Early Medieval' (500–1000) and 'Late Medieval' (1000–1500) periods. I use these terms uniformly, to avoid the confusion of local historical chronologies that give different names to these periods. The turning points in European history for the end of the Roman empire in the West (usually given as AD 476) and for the start of the 'High' Middle Ages c.1000 provide useful anchor points in the chronology, but these divisions are not intended to represent rigid cultural or historical boundaries. For many, the ramifications of the Black Death were significant enough to necessitate a division between the High Middle Ages

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[1] Although omnivory in pigs may be detected through isotopic analysis. See Chapter 3.

and the 'Late' Middle Ages (c.1350–1500). Since only a small amount of the research present here dates after 1350 I have generally considered all post AD 1000 material under the collective title of Late Medieval. The overview presented here is based on the history of the period from the end of the Roman empire to c. 1500 Medieval Europe provided by Le Goff (2007); Winks and Ruiz (2005) as well as The New Cambridge Medieval History, especially volumes 1-5 (Abulafia, 1999; Fouracre, 2005; Luscombe and Riley-Smith, 2004a,b; McKitterick, 1995; Reuter, 1999). A more specific review of the archaeological and historical framework for central Italy will be discussed in Chapter 5.

The two fundamental questions of medieval history were articulated by Henri Pirenne in the early part of the 20th century and remain the major themes of historical and archaeological discussion to this day (see Havighurst, 1976). The first is a question of the degree of continuity of the Roman structures and cultures through the first millennium. Pirenne's own opinion was that the Roman way of life persisted until the Muslim expansion in the 7th century cut Europe off from the Mediterranean, which was the most significant factor behind the early medieval economic downturn (Pirenne, 1937). Attempting to trace this cultural continuity through material remains is one of the major themes of archaeology of this period (Christie, 2006). The second question asks: when (and why) did the economy revive in the High Middle Ages? This development is linked to the re-emergence of cities, which Pirenne attributed to changing social and economic circumstances in the 10th and 11th centuries (Pirenne, 1925).

1.2.1 Antiquity, Late Antiquity and the 'barbarian' invasions

The Roman empire reached its height in the 2nd century AD with large territorial expansion and political stability under the Antonine empires (see Fig. 1.1). Under a succession of short-lived emperors in the 3rd century the Imperial boundaries contracted. Although the economic and political climate improved

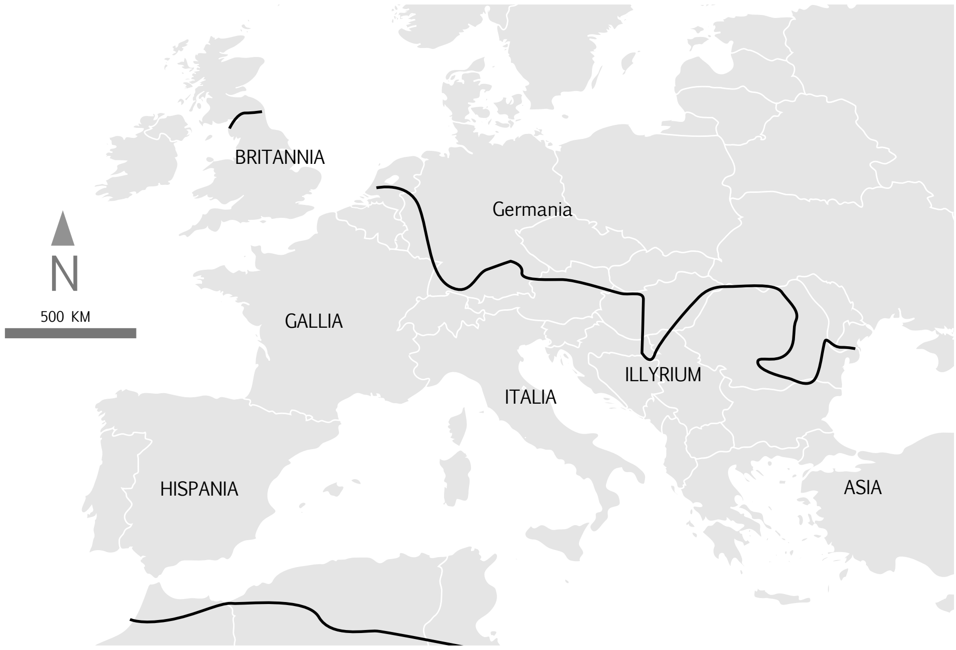

Figure 1.1: *Schematic representation of the maximum extent of the Roman empire, during the reign of Trajan c. AD 117. Major Roman regional names are shown. Redrawn after Potter (2010, xxxi).*

during the reigns of Diocletian and Constantine, the unwieldy imperial administration prompted Diocletian to officially divide empire into Eastern and Western halves in AD 286. The Edict of Milan issued by Constantine in 313 granted Christians the right to worship, and since the emperor himself was now nominally Christian, the new religion gained increasing acceptance. Constantine made the newly-renamed Constantinople his capital, a move which granted the bishop of Rome more independence, and ultimately more power. Theodosius I made Christianity the official religion of the Empire. After his death in 395 the split between the Western and the Eastern Roman empires became permanent.

In the 4th century large numbers of foreigners from central Europe settled within the Roman frontier and were hired as mercenaries in the army. The distinction between Roman and non-Roman became blurred (Whittaker and Garnsey, 1998). In Italy new generals vied for power, and the army eventually proclaimed Odoacer as its king in 472. In northern Europe a number of stable

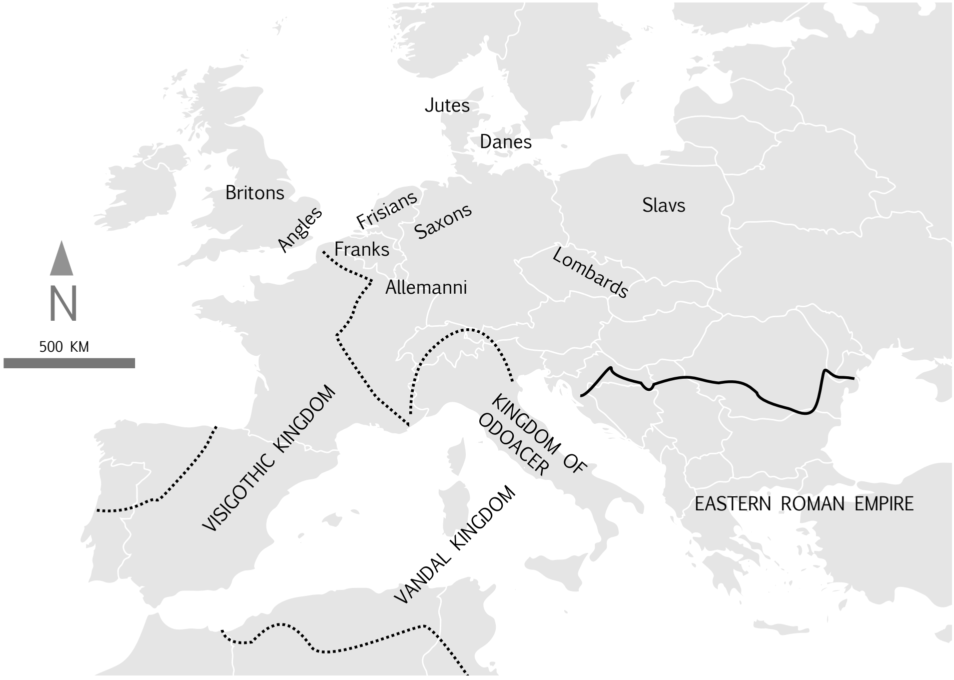

Figure 1.2: *Map of Europe at the fall of the Western Roman Empire AD 476 showing major population movements and political boundaries. Redrawn after Holmes (1988, 9)*

kingdoms arose out of the Iron Age cultures, many of them filling the political vacancy left by the contraction of the Roman empire. As the Ostrogoths took control of Italy, there were Visigoths in Hispania, Franks and Burgundians in Gaul and Germania, Angles and Saxons in Britain and Vandals in North Africa. Saxons, Frisians, Thuringians and Bavarians moved in to fill the vacancies east of the Rhine, while Slavs settled near the Baltic Sea, Bohemia and the Balkans (see Figure 1.2). The final centuries of the Roman empire established many of the economic, political and social patterns that would play a role in the organization of Europe for the next thousand years. Politically, the centre of power shifted away from Rome, both eastward to Constantinople, and northward to new European capitals. Economically, there was widespread contraction in production and trade and depopulation in the West, while the East remained relatively prosperous for longer. Europe became both 'Christianized' and 'ruralized' at this time (Le Goff, 2007). This 'ruralization' will be explored further in Chapter 2.

The Eastern Roman empire, at this point called the Byzantine empire by historians, maintained its political independence and economic stability, although lost many territories. The Byzantine emperor Justinian attempted to reclaim former glory by invading Ostrogothic Italy. The Byzantine–Gothic wars were a series of conflicts that took place from 535 to 554. The Italian population resisted Byzantine invasion for 21 years, but at the cost of huge damage to the countryside and crops. Italy suffered massive economic downturn as a result, including the almost complete loss of the aristocratic elite, who, if they survived, fled to Constantinople or elsewhere. Christie (2006) notes the extent of the impoverishment was such that many 6th-century Italian towns have only the defensive wall and the church built out of stone, with all other structures made of cheaper, more temporary material. There was also severe population decline, both due to starvation and the inability to plant crops, as well as due to a widespread outbreak of plague (see Chapter 2).

Whether they were encouraged to settle in Italy by the Byzantine rulers, or whether they took advantage of a weakened Italian peninsula after the Byzantine-Gothic wars, a new group, the Lombards, made a number of disorganized incursions into Italy. The many Lombard dukes ruled independently of each other for ten years (574–584), failing to elect a king among them. The Italian territory was eventually divided between the Lombards and the Byzantines, with the Lombard duchies mostly autonomous, see Figure 1.3. The Byzantine territories were confined to Rome and Ravenna, and the present-day regions of Marche and Romagna. The Duchy of Rome was jointly under the control of the Byzantine exarch in Ravenna and the Pope in Rome, but the church authorities in Rome controlled a large amount of the territory in central Italy through extensive land donations made in the previous centuries. With the Lombard invasion Rome was increasingly cut off from the representatives of Byzantine authority in northern Italy, and the Bishop of Rome was increasingly the wealthiest and most powerful authority in central Italy. The Lombard duke Zotto took control of most of the territory south of Rome c. 590, creating the

Figure 1.3: *Map of the Europe at the end of the 6th century AD showing major political groups. Political boundaries between Lombards and the Byzantine Empire in Italy have been simplified. Redrawn after Cameron (1993, 35).*

Duchy of Benevento. In the Campagna region around Rome (modern Lazio) the population on the borders between the Romano-Byzantine and Lombard territories became increasingly concentrated in fortified strongholds. When the Lombards conquered the Exarchate of Ravenna in the 750s, Rome was completely cut off from Byzantium, and the Pope called on the help of the Franks to remove the Lombard king Aistulf, ushering in the Carolingian empire.

Pohl (2002) has argued that the new arrivals left very little trace in Italy, and that even by the time of the Lombard kingdom, very little had changed for the rural peasants of Italy, who simply exchanged Roman land-owning aristocrats for Lombard ones. The fact that the Lombards adopted Roman property law for their own legal system points to considerable cultural and economic continuity (Everett, 2000). The invading Ostrogoths and Byzantines probably did not include more than 50,000 males, but would have brought with them potentially large numbers of women, children, slaves and animals. The Lombards, on the

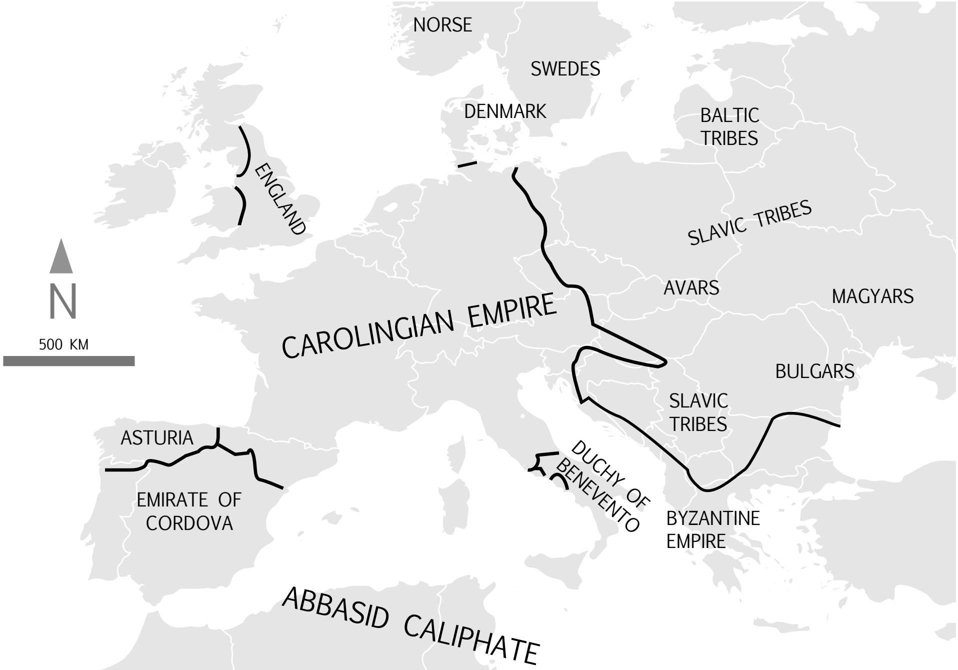

Figure 1.4: *Map of the Europe during the Carolingian empire c. AD 814 showing major political boundaries. Redrawn after Winks and Ruiz (2005, 86).*

other hand, seem to have deliberately settled Italy and may have brought up to 100,000 people (Christie, 2006).

Terms like ‘Goth’ and ‘Lombard’ may not be useful to apply to cultural identity in the past. There could have been significant fluidity in individual cultural identity. A person buried with Lombard-style grave goods does not necessarily indicate how this person viewed himself or herself in life. ‘Lombard’ burials can be distinguished from ‘native’ burials on the basis of their weaponry and metalwork, but Christie (2006) notes that the so-called ‘non-Lombard’ burials are intermingled with the Lombard ones, showing that these people, even if they subscribed to such a dichotomous identity, lived side-by-side. Without textual evidence, the distinction between Roman, Goth and Lombard would be almost impossible.

1.2.2 Carolingian Europe: 8th to 10th centuries

Under the Carolingian dynasty there was a brief attempt at a reunification of Europe, and a flourishing of economic and cultural activity as a result (Le Goff, 2007, 29). The Franks, under their Carolingian ruler Pepin, invaded Italy by crossing the Alps in 754–56. Pepin gave control of Rome and its surrounding territory to the Pope after his conquest. This Donation of Pepin became the basis for papal sovereignty over the area around Rome, which remained independent of other political developments in Italy until 1870. Following a number of other conquests, Charlemagne invaded Italy, conquered, and was crowned emperor and *rex Langobardorum* in 800 (see Figure 1.4).

The empire created by Charlemagne brought a ‘Carolingian Renaissance’ to Europe, with an increase in literacy and artistic production, although the empire was divided by conflicts between his heirs. Louis II divided the duchy of Benevento into two principates, with the principality of Salerno to the south and the Principality of Benevento to the north. The Treaty of Verdun (843) brought peace by dividing the Empire into three kingdoms, Middle Francia in the Low Countries and Burgundy, East Francia or the Kingdom of Germany and West Francia or the Kingdom of France.

Italy continued to be nominally ruled by Frankish kings during the 9th century. The peninsula became increasingly cut off from the Byzantine empire and made renewed contacts with western Europe. But in Italy the post-Carolingian period was also a tumultuous one, where rival kings vied for power. The various regions of Italy had enjoyed a large degree of autonomy under the rivalry between different kingdoms. The territory owned by large landowners grew as small-scale landlords gave up their land to become tenant farmers in return for military protection (Winks and Ruiz, 2005).

One of the most important economic developments in Europe at this time was the political integration of Italy into the rest of Europe above the Alps (McCormick, 2001, 792), linking the economic developments in northern Italy with the growing North Sea trade. Part of the reason for this northward reorientation was due to the expansion of Arabs across North Africa, cutting southern Europe off from the Mediterranean. The Hijra of Mohammed in 622 signaled the rise of Islam in the Middle East and Mediterranean. The Muslim armies conquered a number of territories formerly in control of the Eastern Roman empire, including the Levant, Egypt, Syria and Iraq. Their control extended over the entire area of what had been the Sassanid Persian Empire by the 650s. Under the Umayyad Caliphate (661-750) the rest of North Africa and Visigothic Spain were conquered, as well as the remaining territories of Persia and the Caucasus. Great ports, such as Valencia, arose in Spain as part of the Muslim trade network, while at the end of the 8th century, Muslim-controlled Cordoba was the largest city in Western Europe (Winks and Ruiz, 2005, 73).

Muslim invaders briefly colonized many areas of central Italy, while at the same time the Byzantines reconquered territory at the southernmost part of the peninsula. In 827 Muslims conquered Sicily and ruled there until 1053. The Muslim Arab presence in Italy increased throughout the 9th century, attacking Rome in 846, although they were expelled from southern Italy by a joint campaign of Byzantines and Franks in 915. The Byzantines also reconquered territory in the southernmost parts of mainland Italy. The capture of Sicily by Arabs altered the re-emerging shipping routes, due to the increased the danger of sailing through the Straits of Messina. As a result, Venice concentrated on Eastern markets, giving space for Tyrrhenian cities like Genoa and Naples to capture the Western trade (McCormick, 2001).

1.2.3 The High Middle Ages (11th-13th centuries) and decline (14th and 15th centuries)

The 11th and 12th centuries were a period of significant change for the medieval world which saw the resurgence of Western Europe for the first time since the declining years of the Roman empire (see Figure 1.5.) These developments

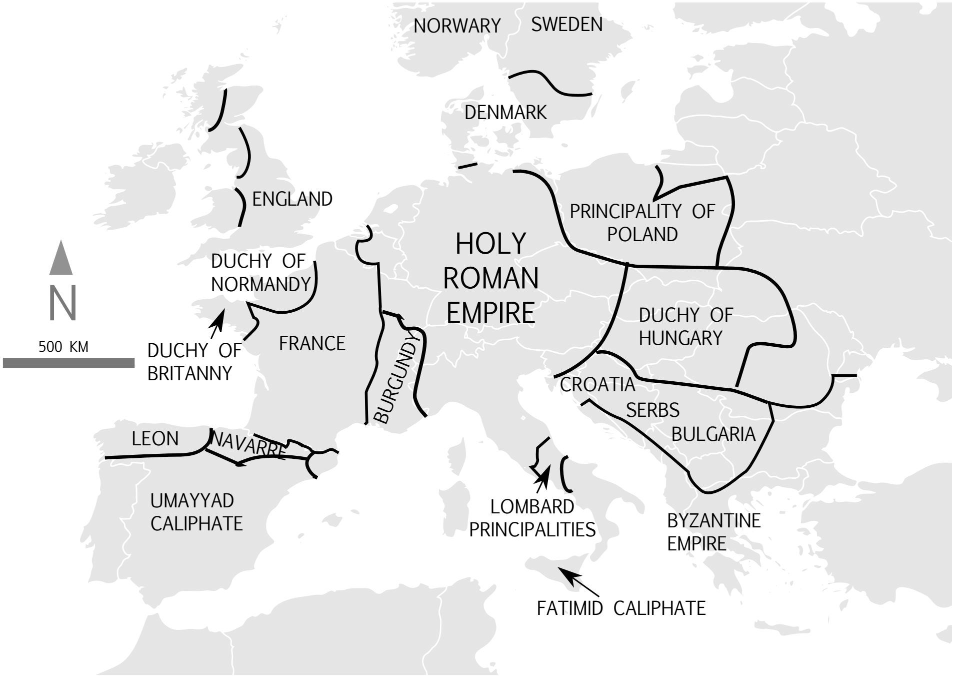

Figure 1.5: *Map of the Europe c. AD 1000 showing major political boundaries. Redrawn after Le Goff (1988, 58).*

were fuelled by economic renewal in the 11th to 13th centuries, although it was beginning in some areas, notably Lazio, from the middle of the 10th century. Toubert (1973) used the term ‘incastellamento’ to describe the reorganization of medieval society at this time, to refer to the feudal organization centred on a fortified location. By the 12th century towns and city-states emerged in northern Italy, and urbanization was also prominent in Flanders and the territory of the Rhine. This urban growth was the result of increased agricultural production and population growth, which itself encouraged the growth of towns and the expansion of trade. New construction, especially of churches, stimulated the growth of craftsmen’s guilds (Le Goff, 2007, 42). Between 1000 and 1300 the European population doubled (del Panta, 1996). This coincided with new technologies, including animal shoeing, animal-powered mills and the wheeled plough (Riera-Melis, 1999).

The Normans created a kingdom in southern Italy, in the territory that had formerly been the duchies of Spoleto and Benevento, starting with conquests between 1041 and 1071, and by 1091 had taken control of Sicily. By 1137 the Normans controlled what came to be known as the Kingdom of Sicily, including the significant city of Naples as well, expelling the Muslims from southern Italy. The kingdom of southern Italy and Sicily was conquered briefly by Charles of Anjou in 1268 and more permanently by the Aragonese in 1282.

In Italy, Milan, Genoa and Pisa emerged as the dominant independent cities. The growth of maritime powers, including the city of Venice is notable in this period. The papal authorities largely regained control of Lazio and consolidated their rule there. With the election of Pope Leo IX in 1049, and encouraged by radical reformers bent on restoring the Christian empire to its former glory, the papacy began challenging the authority of Byzantium. The East-West Schism of the church in 1054 created a permanent geographic, theological and political division between Western Catholicism and Eastern Orthodoxy.

The First Crusade began in 1095. The crusaders' ability to control trading ports in the Holy Land, as well as the capture of Jerusalem in 1099, benefited Italian merchants. The subsequent Crusades (from 1147 to 1272) created a number of short-lived Crusader states in the 12th and 13th centuries. The Crusades and general increase in Arab-European communication brought new products to Europe, including foods like sugar, saffron, rice, lemon, apricots, shallots, scallions, melons and pistachios (see Chapter 2). Iberia was reclaimed by the Christians, who expelled Muslim rulers from the entire peninsula (except the Emirate of Granada) by 1249. The end of the caliphate of Cordoba allowed the Christian kingdom of Castile to flourish (1035–1312). The Byzantine empire was increasingly constrained by enemies on its frontiers as well as by the actions of Western European Crusaders (notably the sacking of Constantinople in 1204 during the Fourth Crusade). The Ottomans expanded into Byzantine territory across Anatolia, the Eastern Mediterranean and the Balkans during the 14th century.

From the 1350s Europe and the Mediterranean suffered a series of crises, including the Avignon Papacy, from 1305–1378 and the Western Schism from

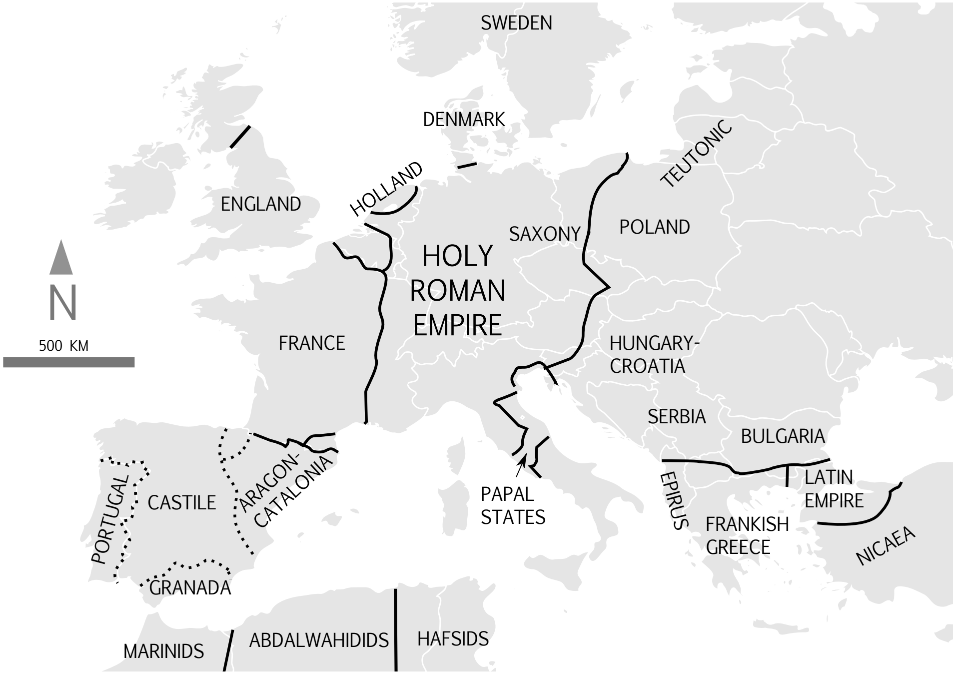

Figure 1.6: *Map of the Europe in the 13th century showing major political boundaries. Redrawn after Abulafia (1999, 3)*

1378 to 1418, a period where multiple people contended for the title of Pope and it was not until the election of Martin V in 1417 that unity was restored. The Black Death likely caused the loss of one-third of the European population, although this varied by region (Le Goff, 2007, 160). Long periods of extreme cold and rain in northern Europe resulted a prolonged famine from 1315 to 1322. Warfare was also more intense in the 14th century, fuelled by the rise of proto-nation-state (see Figure 1.6). The kingdoms of England, France, Aragon, Castile and Portugal vied for power. New military technologies such as cannons and gunpowder saw the rise of professional soldiers. The whole of Europe became increasingly militarized in the 14th and 15th centuries.

This was also a period, however that saw European powers reaching farther afield in international trade. The Genoese and the Venetians both began sailing around the Atlantic to Northern European ports by the beginning of the 14th century. The next stage of European expansion would see a re-structuring of power and resources, and an exchange of New and Old World foods, creating the European dietary habits that are prevalent today.

1.3 Research design and hypotheses

The period AD 1–1500 was one of significant social, political and economic change for Europe. This thesis examines how these changes affected the food-related practices of the average person, in both economic and social terms. The scale of this examination incorporates continent-wide information, using a meta-analysis of previously published data, with a detailed view of dietary change over 1500 years on a local scale in central Italy. Several important observations about how these historical developments would have affected diet can be made, which will be discussed in more detail in Chapter 2:

- The Roman economy was highly integrated. Food production was maximized in central Italy through intensive and extensive strategies, but large amounts of food were imported from Rome's colonies.
- Overland trade was considerably more difficult than maritime trade, and the relationship between urban and rural diets needs to be more fully explored. Diet at inland sites from Roman Italy has not been widely studied.
- New populations moved into Europe, and into central Italy especially, who may have brought new food behaviours and agricultural practices. A Roman food ideology based on heavy cereal consumption can be contrasted with a more carnivorous focus attributed to the invading populations.
- Christianity began to exert a considerable social force from the late Roman period onwards.
- Diminished trade, and decreased population resulted in an economic depression in the early Medieval period. Inland rural areas may have been especially marginalized.

- Urban centres were concentrations of wealth and trade. Levels of urbanization decreased significantly in the Early Medieval period (c. AD 500-1000).
- The economic depression of the early Middle Ages can be linked to environmental and climatic deterioration, but the relationship between these factors and changing agricultural practices is complex.
- Urbanization and trade revived throughout Europe c. AD 1000.
- After AD 1000, increasing trade with the Middle East introduced new foods.
- Throughout all periods dietary choices were limited by status, including economic wealth, but also limited by the age and sex of the individual.

Chapter 2 presents evidence for the argument by Christie (2004, 2006); Duby (1974); Hodges (1982, 1997); Montanari (1988, 1994, 1999b) and Pearson (1997) that: 1) 'Roman' and 'Barbarian' consumption patterns were fundamentally different, and that 2) meat consumption for the average person would have been higher during the economic depression of the Early Middle Ages than in the Roman period previously. The decrease in population in the Early Middle Ages combined with the decline in large-scale trade links would have resulted in a change in economic and agricultural patterns. Arable land can produce more food calories per unit area than pasture land (for a more detailed discussion see Hedges and Reynard, 2007), and the Roman urban market arguably encouraged the production of grain for export. Early Medieval population figures were smaller and so there was less pressure to maximize arable production and fewer opportunities for wholesale trading of surpluses. The decrease of trade would have meant that more rural households in the Early Medieval period relied on a self-sufficient, domestic mode of production (Christie, 2006; Wickham, 1999). Farmers would have diversified their production by raising more animals. Pollen evidence suggests woodland expanded in much of the period 500 to 1000 in Europe. (see Chapter 2). Woodland is excellent habitat for pigs, and historical documents emphasize the important role forested areas had in the production of animals. Other social factors may have influenced the consumption of animal meat such as the influence of central European populations moving into Italy (Goths and Lombards) who were described in Antiquity as especially carnivorous by Roman writers. Lombard law codes suggest the important role that livestock-rearing played in the Italian economy in the Early medieval period while Roman writers emphasize the production of grain.

Previous studies have addressed these questions through pollen, archaeobotanical and zooarchaeological evidence, but these techniques provide only an indirect indicator of what was actually consumed. Stable isotopes measured in bone collagen reflect primarily the protein contribution of the diet, and are especially useful for distinguishing between relative amounts of plant, animal or marine food consumption (see Chapter 3). Stable isotopes reflect not only the food that is eaten, but also the environment in which it is produced. This study is therefore interested in diet change, but also in changes in agricultural practices, two concepts which I link together under the term ‘subsistence’.

The challenge of this research is to disentangle intra-population dietary variability from the generic patterns inferred from historical narratives. The key to minimizing interpretive errors due to population-level variability is to incorporate, insofar as it is possible, population-level data. For this reason the continental-scale meta-analysis is crucial. The meta-analysis is limited by the available data, however, and cannot control for changes in the geographical distribution of sites through time. It is therefore also essential to obtain a diachronic view of isotopic changes over 1500 years within a relatively small area. Thus the question of subsistence change at the Roman-Medieval transition in Europe needs to be addressed on both a continental and local scale. The historical outline given above, and elaborated in Chapter 2, is based on a general view of European economic, political and social developments. But these developments affected individuals to different degrees who adopted different strategies depending on local circumstances. This study seeks to address this local perspective by undertaking stable isotope analysis of individuals from central Italy. The selection of sites (see Chapter 4), was designed to consider the effects that urbanization and proximity to the coast can have on diet. It was designed to select a cross section of samples from the Roman to Medieval transition from inland, coastal, urban and rural areas that would complement the existing stable isotope data from previously published sites. It was also designed to provide information about diet in Lombard-controlled areas of Italy, and to contrast that to Byzantine-controlled areas. In total, 369 individuals and 29 animals were analysed from eight sites, and the results of this isotopic analysis is discussed in chapter 5.

In addition, the broader context of diet change in this period was examined using a meta-analysis of previously published data from nearly 100 sites. This collection represents approximately 2700 and 600 faunal samples from European and Mediterranean sites from the Roman to the late Medieval period (see Chapter 6). The meta-analysis attempts to identify continent-wide isotopic differences, to infer from them subsistence changes, and to determine whether these changes may be linked to the broader historical trends. For both of these levels of analysis the specific hypotheses, predictions and tests are outlined below.

1.3.1 Methodological Questions

As the review of previously published stable isotope analysis of classical and medieval Europe and the Mediterranean in Chapter 6 shows, the common theme of the many studies of Roman diets has been a failure to identify a significant quantity of fish consumption using stable isotope analysis, despite abundant evidence from historical and archaeological evidence that fish consumption may have been taking place.

- Why do stable isotope studies from the Mediterranean show surprisingly little evidence for fish consumption? Do ancient literary sources exaggerate the evidence for fish consumption? How does the current standard isotopic model, which predicts a low-to-moderate level of fish consumption, agree with estimates for ancient fish production capacity and labour?

- Based on recent experiments of amino acid routing, what is the maximum possible masking effect that a low-protein diet could have on bulk stable carbon isotope ratios? Is this a viable explanation for the perceived lack of marine carbon among Mediterranean populations that were expected to consume large amounts of fish? Is this low-protein diet feasible in the context of the ancient Mediterranean?
- What effect does long-term agricultural intensification, soil erosion and over-exploitation have on δ^{15}N? What happens to soil δ^{15}N when crop cultivation becomes less intense? Would these changes be applicable to changing patterns of δ^{15}N in the Roman to late Medieval period?

1.3.2 Trade-related questions

What role did the population decrease of the Early Middle Ages have on the consumption of animal meat by people? Are there changes in the availability of imported foods? Does the availability of marine foods in inland areas change over time? What role do markets and urban centres play in the distribution of bulk food products? This study will answer these questions by examining the following isotopic trends:

1. What are the characteristics of rural diet in Roman Italy? Historical evidence suggests that grain would have supplied the majority of the calories for the poor, which would result in low δ^{15}N values. Are low δ^{15}N values found at rural sites? How does this compare to dietary models based on documentary evidence?
2. How does Roman diet in central Italy differ between inland and coastal areas? If Roman trade were highly integrated, marine products might be expected to reach inland areas in significant quantities. Do inland

areas of Italy show significantly high δ^{13}C and δ^{15}N indicative of marine protein consumption? Diminished trade in the early Middle Ages would be expected to reduce trade of marine products to inland areas. Does δ^{13}C and δ^{15}N in humans in inland Italy change over time?

3. Are there significant isotopic differences between urban and rural sites in Italy? Urban areas were the focus of trade and wealth. Many high-status foods (meat and fish) would have been higher in δ^{15}N. Do humans from urban areas have higher δ^{15}N? Urban sites in Italy tend to be located on the coast. Are the isotopic patterns observed simply due to the geographic proximity of high δ^{15}N marine foods, or are inland urban sites also likely to be high in δ^{15}N?
4. In central Italy, and in the European context as a whole, is there evidence for an increase in meat consumption in the early Medieval period? Are human δ^{15}N higher relative to fauna in the early Medieval period compared to the Roman period?
5. Are there changes in animal and human δ^{15}N over time that could be related to changes in manuring practices or agricultural intensification? Are there changes in δ^{13}C over time that reflect the increasing reliance on C4 crops (millet, sorghum), or changing environmental conditions? Can this pattern be observed across Europe?
6. With the process of urbanization beginning c. 1000, are isotopic differences observed in the populations of central Italy and in Europe in general that could be due to changing diet or agricultural practices?

1.3.3 Social questions

The changes that occurred in Italy affected more than just the economy and availability of food products. The new populations moving into Italy may have brought new dietary practices, especially a diet focused on livestock rearing and meat consumption. The spread of Christianity may have been another contributing factor in diet change. As the teachings of the medieval church became consolidated, so too did the practice of fasting, and especially the recommendation to substitute fish for meat on many days of the year. In inland areas this may have increased the consumption of fish, especially for individuals buried in a religious context.

1. High status foods are generally higher in δ^{15}N, such as meat and fish. Do men have more access to high status food items than women? Are there significant differences in δ^{15}N between males and females?
2. Are there significant isotopic differences between juveniles and adults?
3. Do populations outside the boundaries of the Roman empire exhibit higher δ^{15}N values relative to fauna, which might indicate a greater amount of animal meat consumption?
4. Are there isotopic differences between Byzantine-controlled and Lombard-controlled areas in the early Medieval period in central Italy? Could these be related to dietary differences?
5. Do inter-individual dietary differences become more uniform after AD 500, or are the elite still able to consume a distinct diet?

1.4 Summary

The next chapter discusses the historical and archaeological evidence for diet in Europe and central Italy c. AD 1–1500. The evidence suggests that decreased population, diminished trade and the movement of people in the early Medieval period could have resulted in a general increase in meat consumption. However, the differences between Mediterranean and continental environments and the different agricultural practices that arise from these differences may have been significant. I also present the argument that the need to adapt to local circumstances may have had a more significant effect on subsistence patterns than wider political, economic or social changes through time.

The third chapter reviews the basis and techniques of stable isotope analysis in archaeology. This chapter outlines the uncertainties facing any dietary reconstruction based on stable isotope analysis but also highlights the dietary categories that may be easily distinguished. The review is focused on the non-dietary factors that influence diet, especially geography and climate. These factors may affect isotopic interpretations of diet change in the varied topography of Italy, as well as on a continental scale. I also discuss recent work on the routing of individual amino acids, and how these affect carbon isotope ratios. This has implications for the interpretation of unusually low δ^{13}C ratios in coastal Roman contexts.

The fourth chapter outlines the methodology used for this study. It describes the selection of sites, the definition of the research area and the archaeological context of the samples. I describe the laboratory methods used for collagen extraction and stable isotope analysis. This chapter also includes an analysis of the secondary mass spectrometer data to examine collagen preservation and data quality. The final part of this chapter discusses the design of the meta-analysis of previously published Roman and Medieval isotopic data.

The fifth chapter summarizes the results from the bulk collagen stable carbon and nitrogen isotope ratios. New data from eight Italian sites are presented. These are compared to data from eight previously published result using statistical models. A mixed, multi-level model was chosen in order to account for random inter-site variation and additional factors that vary according to site (Date, proximity to coast) and individual (Age, Sex). The results do not show any evidence for increased δ^{15}N in central Italy in the Early Medieval period, however, other significant differences (male/female), (coastal/inland) are discussed. It was also found that urban sites had significantly higher δ^{15}N compared to coastal sites.

The sixth chapter presents the results of the meta-analysis of isotopic data from Roman and Medieval Europe. A mixed, multi-level model was applied to examine differences according to Date, Location, proximity to coast, Age, Sex and Species. Isotopic ratios of both humans and fauna tend to be lower in the Early Medieval period. It was also found that the Mediterranean had significantly higher δ^{13}C compared to other regions. Other significant trends are discussed, including male/female and coastal/inland differences

The seventh chapter discusses social and economic implications of the stable isotope results presented in Chapters 5 and 6. First, I examine the isotopic evidence for Roman diet in Italy, and present calculations for estimating the amount of animal protein and marine protein in the diet. These estimates suggest that the isotopic data is not consistent with a grain-based Roman economy. I then discuss the wider issue of subsistence change in early Medieval Europe, and examine whether the hypothesis of increased animal meat consumption fits the data presented. The absence of an increase in δ^{15}N does not support the hypothesis of increased meat consumption at the end of the Roman empire. I consider multiple non-dietary factors, including environmental and anthropogenic influences that may affect δ^{15}N. These confounding factors introduce uncertainty in the assessment of diet change at the Roman to Medieval transition. When this uncertainty is considered, it is not possible to eliminate the hypothesis of increased meat consumption, since humans consuming widely different diets could exhibit similar isotopic ratios. The final section of this chapter discusses additional dietary trends related to urbanization and social status.

The final chapter summarizes the conclusions of this study, and examines the effectiveness of this research in a wider context. Despite the uncertainties in dietary reconstructions discussed in Chapter 7, I conclude that the model of an integrated Roman economy dissolving into extremely localized production in the early Medieval period is not supported by the data. The isotopic evidence from Roman Italy supports the alternative view of a less integrated Roman economy, and a relatively high amount of meat consumption at this time. The data therefore also support the hypothesis that agriculture and trade were constrained by immediate geographic and climatic limitations throughout the first millennium AD, and that minimal diet changed occurred.

Food*, of course, is central to history; without it there would be no life, and thus, no history.*

— Kenneth F. Kiple and Kriemhild Coneè Ornelas,
in the introduction to *The Cambridge World History of Food*

2

Roman and Medieval Diet and Culture: Italy, the Mediterranean and Europe

In the introduction, I outlined the historical developments that occurred in Roman and Medieval Europe. In this chapter, I examine in more detail the implications of these developments for subsistence patterns in economic and social terms. I summarize a large body of scholarship which emphasizes the combination of new food identities and new economic circumstances that produced a new 'European' diet in the early Medieval period, one based on significantly more animal meat than in the Roman period. However, regional variations in subsistence practices would have been significant, which may be a complicating factor in attempting to observe any large-scale behavioural change. Although a wide variety of sources provide information about dietary habits, few generalizations can be made with any certainty. It is almost impossible to make quantitative assessments of the relative contribution of animal sources in the diet when sources like faunal bone assemblages are incomplete and written sources are highly selective. Fish bones are especially poorly preserved, and the consumption of fish as inferred from the archaeological record is likely underestimated. There is a limited amount of information about dietary practices that can be obtain from the historical and archaeological evidence outlined in this chapter. Broad social, political or economic changes have no more than an indirect effect on dietary practices. This effect is likely limited by individual circumstances, preferences and resources. As will be discussed in subsequent chapters, stable isotope anlaysis provides complementary data about dietary practices, but one which may reflect more idiosyncratic differences than large-scale historical trends.

2.1 Sources of evidence

2.1.1 Textual evidence

There is a large amount of written evidence for diet and agricultural practices during the Roman and Medieval periods, which can take a variety of forms. Texts on agriculture such as those by Cato (2nd century BC), Varro (1st century BC) Columella, Pliny (both 1st century AD) and Palladius (late 4th century AD) provide information about the types of food available and how it was produced (Garnsey, 1999, 17, 23). Food was also a topic of medical interest in the Hippocratic Corpus (*On Regimen*; 5th-4th century BC) and was discussed extensively by Roman physicians, such as Galen in *On the properties of foodstuffs* (Garnsey, 1999, 101-4, 145). There are also a large number of extant recipe books describing food behaviour, especially among the elite. Roman recipe books include the 1st-century AD *De re coquinaria* by Apicius (Edwards, 1984), and *The Deipnosophists* or 'The Banquet of the Learned', an account of banqueting and recipes based on older texts, compiled by Athanaeus c. AD 200 (Garnsey, 1999, 145). Literature on Arab cuisine begins in the 10th century, and by the 13th century there were a large number of books on cooking, although only three survive today (Goody, 1982, chapter 4). The earliest medieval Italian cookbooks do not appear until the late 13th or early 14th century. These include the *Liber de coquina* written in Naples, which shows influence of Arabic cuisine, and the 14th-century *Libro della cocina* written in Tuscany (Capatti and Montanari, 2003, chapter 1).

Literacy, and especially writing about food, is a practice restricted to the elite, and so this type of direct literary evidence is not representative of the average diet. It is unknown to what extent the accounts and recipes were exaggerated, and how they differed from the actual diet of the average person. Information about everyday diet comes from more indirect sources. Roman legal practices provide evidence for the consumption of certain foods, through sumptuary laws, or the provision of bread (and from the 3rd century onwards, pork) to citizens in the city of Rome. In the medieval period literacy was less widespread, but Lombard law codes continue to provide a sense of agricultural practices (Pearson, 1997). Estate inventories, taxation records and historical chronicles can also be used. Religious texts, monastic rules, and accounts of saints' lives also inform about the medieval relationship with food (Bynum, 1987; Grimm, 1996). These written records can be difficult to interpret, since different subsistence practices may be inferred from similar forms of indirect evidence (Pearson, 1997).

2.1.2 Physical evidence

Here, 'physical evidence' includes all the forms of non-textual evidence that can be used to reconstruct subsistence patterns. Material culture can be studied to uncover trade patterns, and to infer from them changes in subsistence, for example using Roman transport amphorae (Parker, 1973). Artistic depictions can provide a cue, as can the objects, containers and tools associated with food production and consumption. The physical remains of what was actually eaten can be examined from faunal bone assemblages (MacKinnon, 2004) and archaeobotanical remains (Livarda and van der Veen, 2008). Physical evidence does not equally represent all types of food. Some types of subsistence, like cereal production and animal husbandry, are difficult to trace archaeologically, and rely on proxies such as pollen analysis, charred grains, and zooarchaeology

(Lewit, 2009). These sources of physical evidence are nevertheless removed from what was actually consumed. Direct dietary reconstructions are possible because the food that was eaten leaves traces in the human skeleton. Changes in tooth wear patterns or trace elements can be analysed to infer dietary changes. Stable isotope analysis is another direct form of physical dietary evidence, which is the focus of this research.

Integrating archaeological evidence with textual evidence is problematic, since the two forms of evidence are not necessarily related and can confirm or contradict one another (MacKinnon, 2004). The difficulty of creating a dialogue between the largely text-based disciplines of classics and medieval history with the material evidence-based methods of archaeology was addressed by MacKinnon (2004) who took an integrated approach, examining zooarchaeological data in the light of textual references. This study aims to achieve a similar balance.

2.2 Roman Subsistence Patterns

The traditional view of the development of Italian agriculture under the Roman empire describes how the Punic wars of the 3rd and 2nd centuries BC brought new territories under Rome's rule. Wealth and cheap slave labour were brought into Italy. This enabled the cultivation of labour-intensive crops like olives and grapes in the Italian soil, which could be sold for profit in the urban market (Arthur, 1991). A professional army could be used to command more resources abroad to feed a growing population at home, and Rome developed an elaborate food system on this basis (Garnsey, 1983, 1988). From the 2nd century BC onwards, small family farms were combined into large *latifundia* under the ownership of the aristocracy, and agriculture expanded into more marginal areas (Arthur, 1991). As the empire grew, Rome obtained its food supply from the territories that came under its rule, like Egypt and the rest of North Africa (Garnsey, 1983, 1988; Randsborg, 1991). By the 1st and 2nd centuries

AD, the city of Rome was dependent on imported food (Garnsey, 1999, 30). At Rome's port of Ostia, large warehouses were built to store imported food (Vitelli, 1980). Daily markets, as well as those held every nine days, and less frequent fairs, would have distributed food products like grain, meat and fresh fish in large cities and towns (Frayn, 1993).

The classic interpretation is that the Roman economic system, especially in central Italy, was based on large-scale 'open' or extensive agriculture, designed to mass-produce cash crops for the urban market (Christie, 2006, 409-12; Randsborg, 1991). This allowed the Mediterranean's many different ecological zones—mountains, plains, valleys—to be integrated under a single market system (Randsborg, 1991). The complex transport system would have allowed trade in a variety of foodstuffs, including olive oil, wine and processed fish products.

An alternative interpretation places greater emphasis on local geographic and climatic limitations (Horden and Purcell, 2000) and downplays the role of grain, olive or grape cash-cropping in an integrated market system. Roman agricultural practices could have been highly varied: Spurr (1986) identifies no fewer than eight recommended crop rotation schemes from Roman texts, including a legume-based rotation. The variable Mediterranean landscape meant that mixed farming was probably practised by many, according to local circumstances (Horden and Purcell, 2000).

Because of the relative expense of overland transport in the mountainous Italian terrain, food was more easily shipped from distant locations like Sardinia, Sicily, North Africa and Egypt, than it was transported relatively short distances within Italy (Garnsey, 1999, 31). Nevertheless, overland transport did occur, and was facilitated by Roman roads (Horden and Purcell, 2000). However the expense of overland transport meant that in interior areas of Italy, trade remained local even at the height of the Empire, although high-value, easily-preserved items like olive oil and wine would have been more far reaching (Frayn, 1993). That the economies of central Italy remained self-sufficient through the Imperial period is suggested by the lack of imported amphorae in rural Campania (Arthur, 1991).

In the more localized view of the Roman economy, Mediterranean land was intensively farmed with dispersed settlements and heavily-manured fields, compared to the modern system dividing cultivation and pasture, which is less labour intensive but requires more land and nucleated settlements (Halstead, 1987). This type of dispersed settlement pattern has been confirmed by field survey in southern Lazio, including the dispersed finds of potsherds from the 1st century BC to the 3rd century AD indicating that extensive manuring took place in Imperial times (Hodges, 1997).

Sheep and goat rearing could have taken many forms: small-scale animal husbandry with stock kept on a farm, vertical transhumance with seasonal movements to uplands, large-scale transhumance across great distances, or the irregular migrations of nomadic groups (Horden and Purcell, 2000). Animals raised on farms in Roman Italy would have been fed by a combination of cultivated fodder crops, maintained meadows, and rough-grazing, which returned valuable manure to the fields (Spurr, 1986). Manuring would have been necessary to ensure adequate crop yields in Roman Italian soils (Inoue et al., 2009). There is also abundant literary evidence attesting to the widespread use of animal manure during the Roman period, to the extent that a shortage of manure required other nitrogen-rich matter to be applied to fields, such as legumes, human manure and kitchen compost (Spurr, 1986; White, 1970). Spurr (1986) estimates that only about half the land of a Roman farm could have been supplied with manure from stable-kept animals. The rest of the need for fertilizer would have been made up by selectively placing the manure on the poorest soils, and with other forms of compost, green manuring, and fallow fields. Differences in manuring practices have the potential to introduce significant changes in nitrogen isotopic ratios (see Chapter 3.3).

Sheep and goat were the species best suited to the Italian climate, while rearing pigs in sties could have been easily accommodated alongside olive and grape cultivation, a practice common in west-central Italy (King, 1999). The dry summer conditions in Italy meant that large-scale cattle rearing would have been an inefficient use of land more profitably used to grow crops (King, 1999). Cattle are more commonly found in cooler, wetter areas of northern Italy than southern Italy, slaughtered at old ages, and show signs of having been used for labour rather than being raised for meat (MacKinnon, 2004).

In addition to the intensive raising of animals on the farm, historical sources and archaeological evidence (Barker et al., 1991) suggest that large-scale transhumance was practised by the Romans, and the city of Rome was likely well-supplied with pig, sheep and goat driven to the city or butchered and preserved offsite (Christie, 2006, 437). In Imperial times the corridor between Apulia, Molise and Abruzzo would have been used for large-scale transhumance, moving flocks of sheep and goat across large distances to mountain plateaus from summer meadows (Hodges, 1997). This type of transhumance, although it must have always been practised in the upland regions of central Italy's mountains (Barker et al., 1991) was likely not the dominant mode of animal production in the Roman economy (Spurr, 1986). Rather, it was one of the many ways in which the local environmental niches of the Mediterranean were exploited (Horden and Purcell, 2000).

Here, I have simplified models of the Roman agricultural system in Italy into two different types. The debate centres on the relative importance of grain crops, mixed animal husbandry and olive/grape cultivation under the Roman Imperial system (Garnsey, 1983; Halstead, 1987; Randsborg, 1991; Spurr, 1986). The traditional view emphasizes large-scale, extensive agriculture, and the production of cash crops for export to urban markets. The second view emphasizes the difficulties of overland transport and small-scale environmental variation, especially in the Mediterranean. According to this local model, agricultural strategies would have been intensive and diverse, including the rearing of animals for manure and meat. Any contrast between Roman and Early Medieval subsistence patterns will depend on the starting point chosen for the Roman economy. For this reason, it is worth examining in greater detail the evidence for Roman diet, and especially for the consumption of animal products.

2.2.1 Roman diet

Roman agriculture, economy and diet were based on the Mediterranean triad of grain, olive oil and wine, and of the three, historians emphasize the primary role that grains would have played in the diet of the average Roman (Garnsey, 1999, 13-19). Romans consumed a variety of grains, including emmer wheat (*Triticum dicoccum*) for porridge (*puls*), bread wheat (*Triticum aestivum*) and hard wheat (*Triticum durum*, the forerunner of modern pasta wheat). The diverse ecology of the Mediterranean also encouraged the planting of a variety of grains, as did the desire to safeguard against famine (Horden and Purcell, 2000). Carbonized remains from northern and western Europe have shown evidence for six-row barley (*Hordeum vulgare*), emmer wheat, bread wheat, einkorn wheat (*Triticum monococcum*), and spelt (*Triticum spelta*), with oats (*avena sativa*) and rye (*seticum monococcum*) as secondary 'inferior' crops (Spurr, 1986).

Millet is a popular grain for nomadic people, or in times of crisis because it is quick to mature, requires little maintenance (Gyulai, 2006) and is resistant to drought Spurr (1983). The two types of millet that would have been available are broomcorn millet (*Panicum miliaceum*) and foxtail (or Italian) millet (*Setaria italica*). Millet was known from Roman contexts in southern Germany and occurred in small amounts through to the late Middle Ages (Rösch et al., 1992). It has been known in Europe since the Neolithic (Hunt et al., 2008). Written evidence from the classical period describes millet as peasant food, animal fodder or suitable for emergency use only (Spurr, 1983, 1986). Detectable isotopic shifts due to millet have been noted in Bronze Age northern Italy (Tafuri et al., 2009).

Government handouts ensured an adequate amount of grain was available to Rome's poor, imported from North Africa and Egypt (Garnsey, 1983). Information about rations provided to slaves, soldiers and the urban poor suggests that a large proportion of the diet's calories were provided by grain, up to 70-75% (Foxhall and Forbes, 1982; Garnsey, 1998, 1999). Even a diet based on as much as 75% grain would have provided adequate levels of protein due to the high protein content of bread wheat (about 10% by weight), an adequate amino acid distribution and sufficient mineral content, especially if leavened with yeast (Garnsey, 1998).

Although a diet with as much as $^3/_4$ of the calories from grain is theoretically sustainable, Evans (1980) suggests such a figure is too high, even for the poorest peasant. A large proportion of the calories would have come from calorie-dense processed foods like olive oil and wine, while vegetables and fruits would have supplied essential vitamins and minerals. Evans reconstructs a plausible peasant diet where cereals contribute only 55% of the total calories, while animal products (cheese and egg) would have supplied a further 15%, the remainder being made up from high-calorie supplementary foods like wine and olive oil, and additional vegetables and fruit (see Table 2.1). In this estimation, protein levels would have been adequate, at 99g per day (see Chapter 3.6 for recommended protein intake), and about 25% of the protein would have been derived from animal sources, the remainder from plant sources, especially cereals. Dietary calculations like this can verify the plausibility of economic models, ensuring that adequately nutritious subsistence levels are achieved, but it is difficult to verify the accuracy of the dietary estimates themselves. Dietary reconstructions based on stable isotope analysis provide a means of testing the accuracy of such dietary calculations (see Chapter 7).

Legumes would have also been an important source of protein, and their ability to fix nitrogen directly from the atmosphere made them essential for ancient Mediterranean agriculture (Sarpaki, 1992). The species known to have been consumed by the Romans included lentils (*Lens culinaris*), broad beans (*Vicia faba*), peas (*Pisum sativum*) and chickpeas (*Cicer arietinum*). These are all mentioned by writers like Columella, Cato, Theophrastus and Pliny,

Table 2.1: *Reconstruction of hypothetical daily diet for 65kg Roman male peasant by Evans (1980)*

	Amount (g)	Calories (kcal)	Protein (g)
Fruits and Vegetables			
Garlic	10	14	0.6
Carrots	25	10.5	0.28
Figs	25	20	0.3
Endive	25	5	0.43
Mushrooms	25	7	0.68
Parsley	25	11	0.9
Radishes	25	17	1
Walnuts	25	163	3.7
Cabbage	50	12	0.65
Major Staples			
Durum wheat	500	1660	63.5
Wine	700	595	0.7
Egg (chicken)	(2 eggs)	163	12.9
Roquefort cheese	50	185	10.75
Olives	100	338	2.2
TOTAL	1585	3200.5	98.58

and are also attested archaeologically (Flint-Hamilton, 1999). Legumes would have been an important source of food in times of famine and were generally considered a lower class food, although they were not avoided by the wealthy (Flint-Hamilton, 1999; Garnsey, 1999).

Olive oil was likely an important source of calories for the poorest Romans (Evans, 1980; Garnsey, 1998). The consumption of nuts should also not be underestimated, and may have been substituted for flour in poor, rural populations, especially chestnuts (Horden and Purcell, 2000). The Romans cultivated fruits and brought this cultivation to the new areas of Europe that came under their control. These fruits (notably walnuts, plums, apricots, peaches and grapes) would have been important dietary supplements (Gyulai, 2006).

Animal products may have been widely available. Pork was preferred to other types of meat by the Romans, but sheep and goat meat would have also been consumed, as suggested by archaeological evidence (King, 1999). Faunal assemblages from culinary contexts show especially high numbers of pig relative to sheep/goat and cattle in western central Italy (Latium and Campania) from the 1st century BC (King, 1999). Sheep and goats were easily reared in the hilly, dry terrain of the Mediterranean, but were more used for their secondary products like wool and milk (for cheese) than for their meat (Garnsey, 1999, 16-17; Thurmond, 2006). The Latin terms *perna* and *petaso* likely referred to different cuts of salt pork, and were known to have been imported to Rome from distant places like Gaul (Frayn, 1995). Pork and other cuts of meat could have been preserved through dry-curing using salt, brine or through pickling (Thurmond, 2006). A wide variety of bird species would also have been consumed, including exotic species like peacock, ostrich and nightingale that were doubtless only available for the wealthy (Brothwell, 1988).

Wealthy landowners could afford to buy meat or raise it themselves. In central Italy and Rome itself, tax revenues enabled the import of food on a large scale and also reduced the cost of pork so that it was not restricted to upper-class consumption, but widely available to a larger part of the population (King, 1999). In order to supply cities like Rome, pigs would be reared nearby, either raised in sties in nearby villas (such as Settefinestre; King, 1999) or in maintained forested areas (Whittaker and Garnsey, 1998). The poor could buy low quality meats like sausages in urban cookhouses and meat (fresh or salt) was also a staple of the Roman soldier's diet (Garnsey, 1999, 17, 125-6). In the 270s the emperor Aurelian introduced free handouts of pork to the poor residents of Rome, in addition to the grain handouts. Despite these facts, classical scholarship adheres to the notion that meat was not widely consumed in the Roman world: 'It remains the case that there was no mass meat production and no mass meat consumption' writes Garnsey (1999, 17).

The Mediterranean would have provided a natural supply of fish for coastal populations, but historians disagree about the extent to which fish was widely consumed (Curtis, 1991; Gallant, 1985; Purcell, 1995). Although the view that 'most people were farmers, not fishermen' (Garnsey, 1999, 16) may be accurate, fish would have been an important source of amino acids, since cereals have low amounts of lysine, and to a lesser extent threonine (Thurmond, 2006). Methods of preserving fish were needed to make use of the large but only seasonally-available catches that the Mediterranean provided (Horden and Purcell, 2000; Purcell, 1995). In addition, fish would have spoiled quickly in the heat since the liver enzymes in fish break down the muscles after death, allowing bacteria to breed easily (Thurmond, 2006).

This means that if fish were to be consumed by people living away from the coast, it must be processed or preserved, by salting or fermenting. Having preserved whole pieces of fish using salt, the waste products could be used to make sauces and flavourings, such as *garum, liquamen* and *allec* (Curtis, 1991). High salinity prevents rotting, and over several months the flesh of the fish gradually dissolves while the solid remains, including bone, precipitate to the bottom. The clear dark salty liquid becomes a protein-rich condiment (*garum* or *liquamen*), while the precipitated remnants form an edible fish paste (*allec*), similar to the many sauces and pastes known in south-east Asian cuisine today (Lopetcharat et al., 2001; Thurmond, 2006). Apicius, the author of the 1st-century AD recipe book *De re coquinaria* lists over 350 recipes calling for fish sauce as a flavouring for meat, fowl, fish, vegetables and even fruit (Curtis, 1991). The species and size of fish used for *garum* could have varied widely. Small fish were generally added whole, but pieces of large carnivorous fish could have also been used (Thurmond, 2006). Modern Asian fish sauces can be a source of protein (and particularly the amino acid lysine) but they contain about twice as much salt by weight as protein (Lopetcharat et al., 2001).[1] Although *garum* itself may not have made a significant dietary contribution, it is only the byproduct of the wider Roman salt-fish processing industry. Dry-

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[1] The NHS recommends no more than 6g of salt per adult per day, which if it were consumed entirely in the form of fish sauce, would provide 3g of protein.

salted fish and fish paste could provide an even higher source of protein and could have been equally widely available.

Salt fish could be caught in bulk and shipped over large distances, making it a cheap source of protein for the urban poor, while at the same time, fresh fish could have been obtained easily by the elite in urban markets (Wilson, 2006). The size and species of the fish would have also affected the degree to which it was viewed as a luxury item. Small, salt-preserved fish were food for the poor, while large, fresh fish were only affordable by the wealthy (Garnsey, 1999). Freshwater fish could be easily obtained in most areas of the Empire, but it is uncertain how regularly it was consumed. During the Imperial period, fishponds were an important source of freshwater fish for those who could afford them, and were especially suited to those species like eel and mullet that could easily adapt to a fresh or brackish environment (Higginbotham, 1997).

The archaeological evidence for the production of *garum* and salted fish products comes from the excavation of salting factories, as well as from the enormous number of amphorae whose contents were labelled, or in which fish bones were found. Africa, Gaul, and especially Spain were noted producers of salted fish products (Curtis, 1991). Where the influence of Rome spread, so too did the taste for fish, especially for preserved fish products like salt fish and *garum*. One traveller in the Levant in the 4th century AD was able to buy salt fish even in inland areas (Curtis, 1991). Imported amphorae of *garum* are found in German forts of the 1st century AD to feed the Italian troops (Parker, 1973). It was similarly imported to the British frontier in Spanish amphorae. In Britain the amphorae from the early part of the Roman conquest show large proportions of fish sauce but this trend declines from the late 2nd century onwards (Cool, 2006).

In Roman writing about food two themes emerge (Garnsey, 1999, 62-65). The first is the contrast between the civilized diet of the classical world compared to the barbaric diet of foreigners. The foods that were most important to classical identity were those that were the products of labour and were deliberately created, as opposed to barbaric 'wild' foods. For Greco-Roman culture, the bread, wine and oil that could be produced by careful cultivation of the soil was an important social symbol (Montanari, 1999a), and it was this hard physical labour that granted the consumption of these foods a certain moral superiority (Garnsey, 1999, 65). Non-Roman 'barbarians' are perceived as pastoral nomads, living off animal products, especially meat and milk. Gauls, Celts and Germans are all described by classical writers as being heavy eaters of meat and animal products (Gowers, 1993; Dupont, 1999). The second aspect of Roman food culture is the value they placed on a simple, frugal, plant-based diet (Garnsey, 1999, 63). The Romans saw their own diet as a corrupted descendant of purer times, where the elite consumed simple foods like porridge and legumes (Gowers, 1993). Literary and textual evidence indicates the elite did not follow this practice in Imperial times. In reality elite consumption was focused on ostentatious displays of food designed to impress (Dunbabin, 2003, see 2.6 below).

2.3 Early Medieval Subsistence Patterns

The political instability at the end of the Roman empire in Western Europe brought a number of changes. Agricultural output was reduced, population decreased in urban and rural areas, and trade networks collapsed. This was accompanied by widespread agricultural changes in Western Europe in the 5th and 6th centuries (Lewit, 2009). The specialized agricultural production, which had formerly existed to supply the market of the Roman state administration, was transformed into a more diversified, locally-focused strategy of mixed animal husbandry. These new trading patterns and regionalization potentially created new patterns of food distribution (Pearson, 1997).

The diminished population in late Antiquity can be determined from a large number of surveys that document the number of sites from the Roman to early

Medieval periods. Pottery-based settlement surveys show an abrupt (Hodges and Whitehouse, 1983), or at least gradual (Cheyette, 2008), decline in the number of settlements in Western Europe between AD 400 and 600. This process began early in Italy, with coastal and open sites starting to disappear from the 2nd and 3rd centuries due to economic uncertainty (Christie, 2006, 490) and worsened with the increased taxation and decreased administrative support in the 4th century (Arthur, 1991). In Tuscany the number of identified sites in a survey of nearly 2000 square km identified 2521 structures in use from the 1st-4th centuries, followed by 506 from the 4th to 6th centuries, and 201 from the 6th to 8th centuries (Valenti, 2004). The number of rural sites in southern Italy also declined severely between the 5th and 7th centuries (Bowes et al., 2006). Italy's population is estimated to have been cut in half, from 8.5 million in AD 200, to 4 million in AD 700 (del Panta, 1996). However, some of this population loss would have been recovered through immigration of incoming Goths, Lombards and Franks (Costambeys, 2009).

A decreasing number of archaeological sites in late Antiquity could be due to a number of causes. Settlement patterns may have shifted. With a greater emphasis on pastoralism and animal husbandry in central Italy under the Lombards, it may be expected that sites would have been more ephemeral (Christie, 2004; Lewit, 2009), perhaps related to a changing ideology of elite expression (Lewit, 2003). Decreasing numbers of sites could also indicate increasing nucleation, with population levels staying relatively similar (Cheyette, 2008).

A large amount of legislation exists from Late Antiquity dealing with the problem of abandoned lands (*'agri deserti'* and *'saltus'*; Christie, 2006, 422-4; Jones, 1964; Whittaker and Garnsey, 1998). This abandonment coincided with the growth of forests and pasture. The excavation of landscape features and pollen analysis have provided evidence for the conversion of arable land to pasture land in the Early Medieval period, as well as for increasing forestation (Cheyette, 2008). The increasing pasture land was available for cows, sheep and goats, while the forest provided an important habitat for pigs, suggesting that livestock raising and mixed animal husbandry was common. In Italy organized transhumance likely disappeared (Christie, 2006) as animals were being allowed to graze on wild lands closer to home. In Italy there is evidence for substantial woodland in the Late Antique phases of Podere S. Mario, in Volterra (Motta, 1997) as well as in Sorano, Lunigiana (Rottoli and Negri, 1998). A similar pattern of heavy environmental exploitation under the Romans followed by a decrease in arable cultivation was noted in German pollen records (as summarized by Janssen, 1992). Overall, pollen evidence suggests a changing proportion of forests, fields and meadows following the end of the Roman empire (Randsborg, 1991).

Increasing taxation from the late 3rd century onwards, combined with damages due to war, further decreased the productivity of Roman agricultural land by limiting the labour force (Whittaker and Garnsey, 1998). The lack of investment in land, and the decreased need for cultivation (due to decreasing population) meant that marginal lands were abandoned, especially upland areas that were difficult to access and those with poor soils, which would yield a poor return on investment (Christie, 2006, 423). A potential trigger of population decrease could have been short-term reductions in food supply as a result of the political upheavals (Christie, 2006, 57).

The timing and extremity of these changes varies by location. The Eastern half of the Empire benefited from a continuing unified state administration where settlement numbers remained high and market-oriented agricultural production persisted (McCormick, 2001). The occupation of rural villas revived in the 4th century in Spain and Gaul, and slightly later in Italy, with some villas in southern Italy continuing until the 6th and 7th centuries (Christie, 2004). This reconsolidation may itself be the product of the abandonment of many small farms, the agglomeration of settlements and the concentration of wealth belonging to a restricted number of elite (Cheyette, 2008; Randsborg, 1991; Whittaker and Garnsey, 1998).

The combination of political instability, population decrease and decreased agricultural output resulted in a collapse of trade networks. From AD 500–800 food production was largely self-sufficient, with only small surpluses available and limited trading in food (Hodges, 1982; Hodges and Whitehouse, 1983; Ward-Perkins, 2000), what Horden and Purcell (2000) call the 'Early Medieval Depression'. Historians and archaeologists debate the timing and extent of this collapse. According to the 'Pirenne Hypothesis' the Arab conquests of the Middle East and North Africa cut Europe off from overseas trade, reducing it to 'near prehistoric levels of commerce' (McCormick, 2001, 2) from the 7th century. However, the discussion above has illustrated that there is a large amount of evidence for the reduction of trade before this time. This collapse in trade between rural and urban areas and the disruption to long-distance trading networks was a key factor in the collapse of the western Roman empire (Ward-Perkins, 2005).

The large-scale import of foodstuffs into Italy, including grain, wine, oil and fish products initially shifted away from western Mediterranean sources to eastern ones, starting in the 4th century, and then ceased completely by about 600 (Randsborg, 1991). The Italian economy was already disrupted by the time the Lombards invaded in 568 and trade was limited to the coasts and ports, due to the devastating effects of the Gothic wars on the Italian countryside (Wickham, 1999). The declining wealth and mobility of the aristocracy resulted in a complete change of urban and rural settlement patterns (Christie, 2006). Lombard-controlled areas were cut off from the rest of Italy, and these ongoing political divisions restricted the movement of goods and people between different areas (Costambeys, 2009; del Panta, 1996).

2.3.1 Central European food identity

The new populations moving into Europe, especially Italy, may have played a role in the changing food practices. While the Romans upheld bread as a symbol of civilization, the incoming central European populations valued meat as a symbol of the warrior and hunter (Montanari, 1988, 7). Greco-Roman writers employed a stereotype of an uncivilized pastoralist barbarian society. Strabo's depiction of Gauls describes them eating meat on the ground, surrounded by herds of animals, while Caesar's Germans eat only animal foods (Garnsey, 1999, 67). The new populations moving into central and southern Europe brought this meat-centred ideology with them. In the Middle Ages, rather than being a sign of poverty, exploiting wild foods becomes the preserve of the wealthy (Montanari, 1999a).

Romans had been in contact with many of these cultures for centuries. Romans were also more willing to absorb foreign cultures than the Greeks, including food behaviours, and so the division between Roman and non-Roman food identity is not a simple one (Gowers, 1993; Dupont, 1999). Montanari (1988) argues that the 'Germanic' and 'Roman' food cultures mixed together to give rise to the mixed production modes and dietary models of the Middle Ages. Grain and vine culture moved north, partly through the influence of Christianity (Duby, 1974, 18), while the 'Germanic' way of living moved south, and brought with it the idea of exploiting the economic potential of wild areas. In this new mixed 'agro-sylvo-pastoral' system, meat and fish developed a new social importance as well (Montanari, 1988). Montanari goes on to note, however, that this meat-oriented food ideology would have been tempered by Christian ideas of fasting.

2.3.2 Christianity and Food

Christianity brought a new perspective to food consumption in Europe. Classic Greco-Roman religious practices were not concerned with restricting food through dietary prohibitions or fasting (Grimm, 1996). The classic Mediterranean triad of bread, wine and oil assumed new prominence with a symbolic role in Christian rites (Garnsey, 1999, 121; Montanari, 1988). This adoption encouraged the spread of these products outside the Mediterranean to the rest of Europe (Duby, 1974, 18). In the Carpathian basin, for example, archaeobotanical evidence for viticulture is associated with the official adoption of Christianity (Gyulai, 2006).

Christians were defined by their relationship with food: they must fast on certain days and must receive communion at least once a year (Bynum, 1987). The earliest Christians saw shared meals as an essential part of their community, which grew into the formal celebration of the Eucharist (Grimm, 1996). The idea of fasting had not been present in Roman religion, but derived from older, Eastern practices (Albala, 2000; Grimm, 1996). Fasting, as opposed to dietary prohibitions, were used to distinguish the growing Christian community from Jews, and at the same time was a useful means of limiting the temptation to sin. (Grimm, 1996).

The ascetic lifestyle was promoted by Saints Jerome and Augustine, although the average person was obliged only to periodically abstain from meat and wine in the 5th century (Grimm, 1996). Fasting became formalized through monastic rules. St Benedict created a regimen of fasting at the monastery of Monte Cassino in central Lazio in the 6th century (Christie, 2006, 166-7). The Benedictine fasting rules and other similar rules became standard in monasteries across Europe. They allowed for two cooked meals per day, and a third of fresh fruit or vegetables where possible, along with two glasses of wine. These fasting regulations prohibited the consumption of meat from four-legged animals for up to $^1/_3$ of the days of the year (Hagen, 1993, 127-134). Rouche's (1987) reconstruction of monastic diet in 8th and 9th century France provides generous quantities of food (see Table 2.2). Pearson (1997) has pointed out the unrealistically high amount of calories this reconstruction provides, although basing my calculation after the caloric yields from milled flour provided by Evans (1980) reduces the caloric estimate somewhat. This diet is nevertheless more than adequate for sustaining an active adult male, In this estimate, animal protein provides $13 - 14\%$ of the total amount of protein, which is much less than Evans' estimate for the Roman poor of about 25%, although Evans estimate includes a greater proportion of vegetables, fruits and nuts.

Table 2.2: *Reconstruction of Carolingian monastic diet by Rouche (1987)*

	Men			Women		
	Amount (g)	Calories (kcal)	Protein (g)	Amount (g)	Calories (kcal)	Protein (g)
bread	1780	2954.8	113.03	1440	2390.4	91.44
wine	1550	1317.5	1.55	138	117.3	0.14
cheese	100	370	21.5	70	259	15.05
legume puree	230	379.5	19.32	133	219.45	11.17
TOTAL	3660	5021.8	155.4	1781	2986.15	117.8

Weight of bread is given as a baked loaf. Assuming half the weight is flour, I use Evans' (1980) ratio of calorie/g flour of 3.32, and his estimate of flour containing 12.7% protein by weight. Legumes are assumed to represent a cooked weight.

Through the course of the early Medieval period, fish became increasingly used as a substitute for meat during Christian fasts (Pearson, 1997). By the late Medieval period in England, Christian fasting practices prohibited the consumption of meat on up to 182 days of the year, increasing the demand for fish (Woolgar, 2000). The records of the Benedictine Abbey at Westminster make it possible to estimate that during Lent fish (mostly sea fish) would have accounted for 18% of the monks' calories. With the remaining 45% and 32% coming from bread and alcohol. Müldner and Richards (2007b) estimate that marine resources would have contributed half of the protein content of the diet during fasting. Several isotopic studies of medieval contexts find higher indications of fish consumption among monastic populations compared to lay populations (see Chapter 6).

2.3.3 Early Medieval Diet

As a result of these economic and agricultural changes, many historians and archaeologists argue for the re-orientation of agriculture towards a strategy focused on mixed animal husbandry, what has been called a 'sylvo-pastoralist' model (Christie, 2006; Duby, 1974; Hodges, 1997; Montanari, 1988, 1999b; Pearson, 1997). Despite the general picture of these changes, there would have been regional variations. In southern and central Italy during the early medieval period (AD500–1000) the diet would have been based on plant foods, especially grains, legumes, fruits and vegetables, with smaller amounts coming from meat and secondary animal products (Montanari, 1988). Arthur (2004) argues on the basis of zooarchaeological evidence that in late Antique Italy pork was only consumed in large quantities in cities like Rome and Naples, and then only until the end of the 6th century, after which time consumption declined significantly. He suggests that the late Imperial emphasis on pork reverted to a diet based on cereals and the meat of sheep and goat, which were less labour-intensive products than pork. In late Antiquity faunal assemblages show increasingly regional consumption patterns, where north and central Europe diverge from the Mediterranean (King, 1999). Despite the economic and political changes, there is evidence for the continuation of some aspects of Roman life. The continued use of processed fish products is known, both from textual sources such as Alexander of Tralles writing in the 6th century AD about the medicinal applications of *garum* (Curtis, 1991) and from archaeological evidence (Trakadas, 2005).

Demand for pigs in Rome likely continued until the Gothic wars in the mid 6th century. For example, it is at this time that the economic activities centred around the rearing of pigs for market at San Giovanni di Ruoti decline along with the rest of the villa (Barnish, 1987). At this site, over 60 percent of the faunal bones were identified as pig. Intensive pig foraging was likely practised, perhaps at the expense of food crops, in order to supply the nearby Roman market. The presence of a small number of marine shells at this site provides evidence for contact with the sea, which would have been the source of the salt essential for meat preservation (MacKinnon et al., 2002; Small and Buck, 1994). However, on urban and rural sites in the rest of Italy, most of the archaeological evidence points to an earlier decline in pork consumption, in the 4th and 5th centuries (King, 1999). King suggests the reason for this late Imperial shift away from pork production to more sheep and goat consumption could be related to a decline in trade and market profitability, with a reversion to a more locally-oriented self-sufficiency, This decline occurred earlier for rural sites in central Italy than it did in the cities, which were able to maintain their high pork consumption for longer.

The legal attitude of the Lombards, as reflected in the *Lex Salica* emphasizes cattle and pasture land, suggesting that animal products were important economically (Pearson, 1997). It has been suggested that Lombard peasants would have eaten meaty stews regularly, which would have been a substantial protein source, and indeed that peasants of early Medieval Europe enjoyed greater access to animal meat than in any previous period (Flandrin and Montanari, 1999). In Italy, documentary evidence indicates that pigs were commonly raised in Lombard-controlled Emilia, but in the neighbouring Romania region, under Byzantine/Roman rule, the traditional sheep pastoralism was more common (Montanari, 1988, 13). Other documentary sources refer to an increase in cattle and horses, reflecting a larger amount of pasture land as opposed to arable land in central Italy in the late Empire (Whittaker and Garnsey, 1998).

Pollen and archaeobotanical studies suggest that there is further evidence for small-scale diversification of crops at the start of the Medieval period, with localized increases in rye, flax and buckwheat in France, Italy and Britain (Cheyette, 2008). The Roman farmer was concerned with creating a high-quality grain product for the urban market, but the Medieval farmer was more self-sufficient, and used a variety of grains depending on local conditions. In southern Germany the popular spelt and bread wheat of the Roman period are replaced by a variety of crops (rye, barley and oats) in the Migration period and Early Medieval period (c. 300–1000; Rösch et al., 1992).

Rouche (1987) estimated the diet of non-monastic peasants in Carolingian France (see Table 2.3). His estimate includes a broad range of between 2000

Table 2.3: *Reconstruction of Carolingian lay diet (low- and high-estimates) by Rouche (1987)*

Low-estimate				High-estimate		
	Amount (g)	Calories (kcal)	Protein (g)	Amount (g)	Calories (kcal)	Protein (g)
bread	360	597.6	22.86	1700	2822	107.95
wine	570	484.5	0.57	1450	1232.5	1.45
beer	570	250.8	2.68	2300	1012	10.81
cheese	35	129.5	7.53	102	377.4	21.93
legume puree	218	359.7	18.31	362	597.3	30.41
fat/meat	102	249.9	17.34	410	1004.5	69.7
TOTAL	1855	2072	69.29	6324	7045.7	242.25

Weight of bread is given as a baked loaf. Assuming half the weight is flour, I use Evans' (1980) ratio of calorie/g flour of 3.32, and his estimate of flour containing 12.7% protein by weight. Legumes are assumed to represent a cooked weight. Nutritional values are based on the USDA Nutrient Database SR18.

and 7000 calories per person, which also includes a provision for animal meat or fat. Since Rouche's dietary calculations provide an unrealistically high maximum caloric estimate, I suggest they are instructive only insofar as they enable an assessment of the relative amount of protein from animal sources. In the reconstruction here I used the nutritional values for a whole pork leg to estimate protein from the meat/fat category. The amount of animal product allotted (meat/fat and cheese) is similar for both the low-end and high-end estimate (36% protein from animal sources for the low-end, 38% for the high-end), which is higher than Evans' estimate of about 25% for the rural poor in Roman Italy, and is comparable to the amount of protein in more elite Roman diets (Cummings, 2008).

The shift toward increasing meat consumption has been investigated using skeletally-based dietary reconstruction techniques. Belcastro et al. (2007) examined patterns of dental wear and tooth pathologies in populations from the Molise region, a mountainous area of central Italy. They concluded that the Romans ate more carbohydrates than their medieval counterparts, due to a greater prevalence of dental caries present in the Roman sample, and that they ate less meat, as indicated by the smaller amount of dental calculus. However, the opposite pattern was found elsewhere. Manzi et al. (1999) looked at patterns of dental-alveolar lesions in two Roman sites and one Medieval site in central Italy (Lazio). They analysed Lucus Feroniae, a group mostly consisting of ex-soldiers and slaves from a rural town (1st to 3rd century AD), the middle-class Roman Imperial sample from Isola Sacra (1st to 3rd century AD) and the 7th-century Lombard necropolis of La Selvicciola. They found that based on their indicators of dental health and diet quality, the Isola Sacra sample had the best diet and health, and the Lombard necropolis the worst. The number of dental-alveolar lesions at the two Roman sites was lower than the Lombard necropolis, suggesting the diet had become increasingly carbohydrate-rich in the Middle Ages.

2.4 Late Medieval Economic Revival

The late Medieval economic revival began as early as the 7th century, with the political stability and renewal of trade under the Carolingians. Estates and monasteries became centres of production, and began to create surpluses (Hodges, 1997; McCormick, 2001). By the 9th century, previously separate economic systems in northwest Europe became increasingly integrated, by creating and redistributing surpluses of staple goods (McCormick, 2001). This was partly due to a revival of agriculture, and the deliberate creation of a market-based economy through a network of trading ‘emporia’ in northwest Europe under the Carolingians (Hodges, 1982). The increase in trade and urbanization is attested archaeologically, with a rise in nucleated farm settlements in northern France from the mid-7th to 8th centuries (Peytremann, 2003), new landscape patterns of central villages surrounded by radiating road networks in France and a shift toward more intensive grain cultivation from the 7th century onwards in the Rhine and in northern France (Cheyette, 2008). This Carolingian economic revival was temporary, especially in Italy, and ended with a return to political chaos (Hodges, 1997). Although the early 9th-century agricultural changes may have been a crucial development for European socio-economic changes (Hodges, 1982), the settlement patterns did not stabilize until the 10th century (Randsborg, 1991).

In Italy the economic changes of the late 10th century are characterized by a consolidation of fortified villages on defensible hillsides, a process known as 'incastellamento' (Toubert, 1973). Incastellamento maximized arable production through a more efficient organization of farms and distribution of surplus, which was often directed towards monasteries (Hodges, 1997). The early Medieval sylvo-pastoralist system was abandoned. The rising population, expansion of arable land and increasing control over territory meant that the average peasant had less access to meat (Hodges, 1982; Montanari, 1999a). This return to a market economy is reflected in the return to a more uniform crop strategy (Rösch et al., 1992). By the 14th century, complex market and supply structures were in place at urban centres (Spufford, 2003). In the Mediterranean, the influence of Arab agricultural practices was profound, and many new plants were introduced during the Medieval period, notably sorghum—a C4 grain used more commonly for animal fodder than for human consumption (Watson, 1974).

In Britain, this economic revival, especially of urban areas, can be pinpointed to within a few decades of AD 1000 due to the sudden increase in the consumption of marine fish, reflecting both the market demand, and the trade networks to supply the fish from the North Sea and the Atlantic (Barrett et al., 2004a). By the 14th century, the more affordable and transportable Atlantic fish began to reach Italy, made possible by the Genoese and Venetian merchants who created trading links with the Atlantic around 1300 (Lane, 1973).

2.5 Changing climates

The period of study between AD 1 and 1500 was not only a significant period of political and social change. There is also abundant evidence for changing climate in Europe and the Mediterranean during this period. There are strong suggestions that the political and population collapses are linked to adverse climatic conditions.

The Roman Warm Period c. 200 BC to AD 400 was a period of relatively warm and stable climate for Europe and the Mediterranean, although the climate became increasingly variable from the mid 3rd century onwards. The Roman Warm Period coincided with the expansion and flourishing of the Roman empire. This can be observed from tree-ring reconstructions of summer precipitation and temperature in central Europe (Büntgen et al., 2011; see Figure 2.1) and in reconstructions of sea surface temperature in the Adriatic from dinoflagelate cyst records (Chen et al., 2011). The dates of felling of the available oak chronologies also suggest that there was increased construction activity during the late Iron Age and Roman empire, with a reduction in tree use from AD 250 to 400. The same study showed that from AD 250–600 there was increasing climatic variability (Büntgen et al., 2011; see Figure 2.1). There was a general decrease in temperature and increase in precipitation in central Europe, but also more extreme variation. Note from Figure 2.1 how oak tree-ring widths suggest an abrupt dry period in the 3rd century in central Europe. Evidence for increased rainfall in the Mediterranean comes from the increase in flooding of the Tiber and in the Apennines from the 5th to the 8th centuries (Giraudi, 2005). In the 6th and 7th centuries Switzerland's Altesch glacier reached nearly the same extent as it did in the coldest parts of the Little Ice Age (Holzhauser et al., 2005). This coincides with documentary evidence suggesting that temperatures dropped in Italy and the rest of Europe while precipitation increased after AD 500 (Randsborg, 1991).

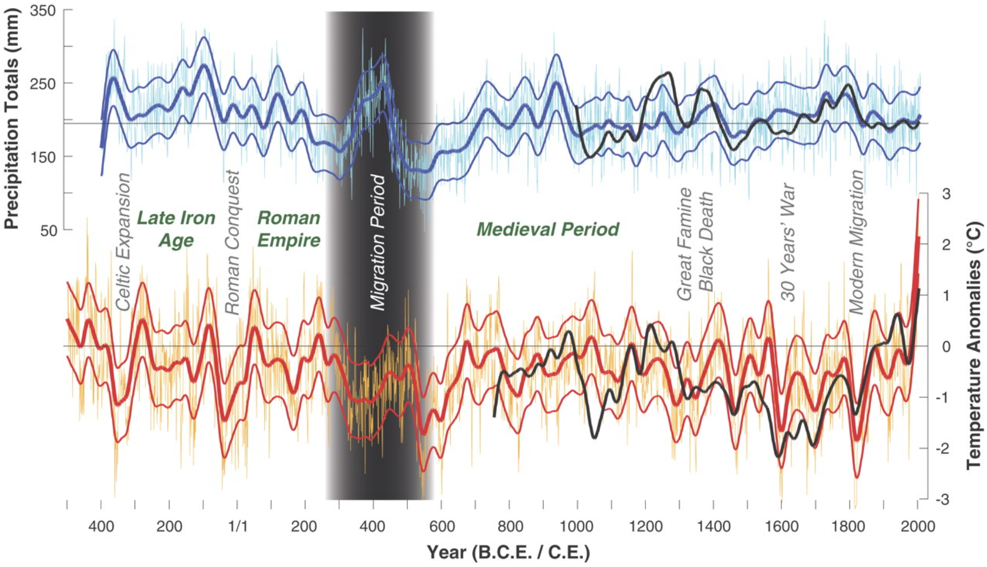

Figure 2.1: *Reconstruction of June-July-August temperature and April-May-June precipitation changes in central Europe in the last 2500 years based on regional oak chronologies, ©Büntgen et al. (2011).*

These climatic changes may be partly related to changes in the mode of the North Atlantic Oscillation (NAO), a pressure gradient between the Azores and Iceland. A positive NAO is defined by high pressure over the Azores, which results in warm air being transported to continental Europe. Winters are mild and wet while summers are cool. In a negative NAO phase, weather patterns are more extreme in central Europe, while the Mediterranean has higher temperatures, and increased precipitation due to more storm activity. A regular cyclical shift in the NAO may be responsible for cyclical river discharge rates observed in Italy (Chen et al., 2011). An equatorial volcanic eruption in AD 536 also contributed to a sudden severe temperature decrease, observed in tree rings, ice cores and historical records (Larsen et al., 2008).

The concurrence between this early medieval cooling and the political changes in Europe is highly suggestive. Cheyette (2008) argues that the critical period of settlement pattern change in the 5th to 7th centuries coincided with this early medieval climatic anomaly, suggesting that the two are linked. A small environmental change could have had a large effect when combined with soil erosion, political instability, plagues and volcanic eruptions. Population levels also would have been affected by the changing climate more directly. Zhang et al. (2011) link historical evidence of population collapse with climatic records and suggest that up to 90% of population collapses in the last 1200 years were linked to deteriorating climate. This is because the carrying capacity of the land is strongly affected by climate. In temperate regions of Europe a cooler climate decreases the amount of land available for growing and reduces crop yields by shortening the growing season (Galloway, 1986).

The early Medieval cooling was relatively short-lived. From the 6th century onward both precipitation and temperature increase in Central Europe, and are the same as Roman conditions by the 9th century (Büntgen et al., 2011). This was the start of the Medieval Climatic Anomaly, or Medieval Warm Period which lasted from c. 800 to 1300. This period coincides with a prolonged period where the North Atlantic Oscillation was generally positive (Trouet et al., 2009). This brought warm wet summers to central Europe, which coincided with political stability and population growth at this time (Büntgen et al., 2011; Zhang et al., 2011).

Changing climate would have affected the amount of land suitable for growing crops, but this could have also changed through time due to deliberate deforestation. In the Rhone valley there is an increase in sedimentation rates associated with deforestation following an expansion of construction in the 3rd century, as well as in the 9th century (Arnaud et al., 2005). Kaplan et al. (2009) modelled rates of deforestation in Europe over the last 3000 years, incorporating a variety of estimates, including population density and soil quality. They note that although the general pattern is one of increasing deforestation over time in the Mediterranean, the period after the collapse of the Roman empire was an exception. This period, along with the period following the Black Death in the 14th century, saw significant amounts of forest growth.

2.6 Diet and Status

2.6.1 Sex-based dietary differences

Sex-based dietary distinctions are common in many modern cultures, especially when women are considered non-contributors to household income (Goody, 1982; Sen, 1990). Reasons for these dietary distinctions can be complex, and are not necessarily the result of an explicit inequality. A sex-based division of labour can result in men and women occupying different physical spaces, with access to different foods (Reitsema et al., 2010). A restricted diet can also be self-imposed. Among the LoDagaa and Gonja of northern Ghana, sex-based differences in meat consumption are widespread, and women consistently give larger portions of meat to men than to themselves (Goody, 1982, 68).

The social hierarchy of the Roman household would have restricted the amount of food available to women. The patriarchal Roman social organization meant that women were allocated a smaller proportion of the family resources (Garnsey, 1999, 100-12). Medical writers advised women to eat as little as possible and to avoid those foods that were perceived as the most nourishing, especially meat (Garnsey, 1999, 102-3). Garnsey argues however, is that this systematic bias against women is more likely to reflect the fact that women genuinely have a lower caloric need ($15 - 35\%$ less) than men.

Food restriction for females was also common in the Middle Ages. Bullough and Campbell (1980) explain the relatively short longevity of women compared to men in the early Medieval period as the result of poor nutrition and frequent pregnancies combining to produce iron deficiencies. Women in particular were drawn to fasting and starvation as a means of religious expression, and as a way of controlling sexual appetites. Women practised fasting more frequently than men, perhaps because they were largely powerless, and this was one of the few means of religious expression that was available to them (Bynum, 1987).

Rouche's (1987) calculation of dietary allowances for men and women in monastic context in 8th and 9th century France also reveal sex-based dietary differences (see Table 2.2 above). Women are allocated only 60% of the calories of men, but these differences may reflect realistic needs based on differences in body mass and activity rates. The differences, rather than reflecting explicit status differences, may be the result of sex-based labour divisions, as suggested elsewhere (Reitsema et al., 2010). Both men and women are allocated similar animal protein fractions in Rouche's estimate ($13-14\%$ animal protein relative to total protein by weight) while men actually receive a proportionally smaller amount of protein based on calories (12% of total calories coming from protein) compared to women (16%).

2.6.2 Elite versus non-elite

As discussed in Chapter 1, the socio-economic status of an individual plays a crucial role in determining the diet they are able to consume. The poor likely always had a relatively low amount of meat and fish in their diets (Hagen, 1993; Hodges, 1982; Rouche, 1987), however Capatti and Montanari (2003) and Montanari (1988, 1999a) argue that meat consumption among the poor would have been highest in the early Medieval period. The absolute differences between elite and poor may have become smaller following the end of the Roman Empire. These social distinctions in diet would have been greater in urban areas compared to the countryside, because the elite would have lived in the urbanized areas that remained during the early Medieval, which were the focus of the limited amount of trade that occurred (Albala, 2000; Costambeys, 2009).

Roman cuisine was especially marked and hierarchical (Garnsey, 1999) which reflects a high degree of social stratification (Goody, 1982). The Roman elite distinguished themselves by their elaborately displayed dining habits (Dunbabin, 2003), through the consumption of specifically elite food, such as fresh marine fish (see above) or by selecting the most highly valued cuts of meat (King, 1999). Similarly, despite the fasting regulations imposed by Christianity, the elite in Medieval times were able to distinguish themselves by continuing to consume high status foods, such as exotic types of fish (Dyer, 2000).

Trace element analysis of skeletal remains from northern Italy has concluded that there were dietary differences between Roman and medieval sites, due partially to status differences. Busetto et al. (2008) used Sr/Ca and Zn/Ca ratios to reconstruct relative amounts of meat consumption. They studied a Roman necropolis from Milan (1st century BC to 2nd century AD), the communal burial of the ruling Lombard family in Campione d'Italia (7th to 9th century AD) and the medieval necropolis of the local Lombard community, near Cremona (7th century AD). They concluded that the Roman Milanese sample had abundant animal protein in their diets, and that while the elite family burial from Campione d'Italia did as well, the rural peasant community ate less meat. Similarly, the isotopic results from the study of early medieval Weingarten in Southern Germany by Schutkowski et al. (1999) differed between individuals with higher- and lower-status grave goods. The results were interpreted as indicating the consumption of higher status foods corresponded with higher status grave goods.

2.6.3 Regional differences in diet

Within the region represented by the 'Roman empire' and 'Medieval Europe' there are fundamental geographic and climatic differences. These differences dictate agricultural practices and hence the types of food that were eaten (Horden and Purcell, 2000). The area under study is divided between the warm, arid climate of the Mediterranean, with its mountainous geography and heavy winter rainfalls, and the more temperate climate and heavy soils of continental Europe (Randsborg, 1991). Within the Mediterranean zone there is significant variation, however, and Italy receives more rain than many other places (Horden and Purcell, 2000). In the Mediterranean as a whole, aridity is a significant limiting factor for agriculture, but less so in Italy's comparatively wet climate.

Zooarchaeological evidence shows that different areas of the Roman empire focused on different animals. Regional differences, part geographical and part cultural, played a strong role in the choice of which animals were raised and consumed (King, 1999). Northern and central European Roman provinces (Britain, northern Gaul, Germany and the Danube region) show high relative proportions of cattle, while in hot climates (Spain, North Africa, southern Gaul, Greece, Asia Minor, Egypt and the Near East) sheep and goat are more prominent (King, 1999). Despite the tendency for larger amounts of cattle than other regions of the Empire, in Britain there is a clear trend toward increasing consumption of pig and sheep/goat on Romanized sites, while pig was not popular among the indigenous Britons (Cool, 2006).

Differences between urban and rural areas may also have been important, because the urban poor throughout the 1st millennium would have had access to different dietary resources than their rural counterparts, such as fish (Barrett et al., 2004b; Nutto, 1995). Meat would have arguably been more expensive in cities, and so may have been consumed more widely in rural areas (Garnsey, 1983). Yet, some zooarchaeological evidence shows similar patterns of distribution of pig, sheep/goat and ox bones in Roman urban and rural sites (King, 1999). However, there is also evidence that better quality cuts of meat were exported to cities, while rural sites retained the less valuable cuts for their own consumption (MacKinnon, 2004).

2.7 Diet and culture in Roman and Medieval Italy: conclusions

The above information about economic, agricultural and dietary change in the Roman and Medieval period can be distilled into two arguments. The first is that meat consumption for the average person would have been higher during the early Medieval economic depression than in either of the preceding or succeeding periods. This argument is based on a number of assumptions. It assumes that the Roman economy was under pressure to feed a large population, and that animal products would have been less available, since these require relatively more land to produce per unit energy yielded compared to crops. It also assumes that the market pressures and trade networks were substantial enough under the Roman empire to ensure that individual producers were integrated into the wider exchange system. During the Early Medieval economic depression, in the absence of both population pressure and trade networks, greater opportunities for rearing animals were created, and consumption of animal products increased.

The relationship between increasing meat consumption and decreasing population pressure (and economic downturn) has also been hypothesized for the Greek Dark Age, c. 800 BC (Sallares, 1991) and for Europe after the Black Death (Braudel, 1973, 128). For early Medieval Europe, this theory is substantiated by evidence for increasing references to animal husbandry and meat consumption in documentary sources, and by zooarchaeological evidence for high frequencies of animal products. The evidence for increasing afforestation in the early Medieval period suggests habitats for game and pigs were abundant, while less land was cleared for crop production. However, studies which have attempted to make a direct comparison by estimating relative amounts of meat consumption in Roman and early Medieval skeletons in Italy have reached contradictory conclusions.

This suggests that there may be problems with the hypothesis of increasing meat consumption in the early Middle Ages. The sources of evidence used to support this hypothesis are drawn from across Europe, with evidence from a particular location often being extrapolated to an entire continent. As described above, there is good reason to suspect that regional differences, especially between continental and Mediterranean zones, would have imposed limitations on subsistence strategies. In this case the dietary transitions discussed simply reflect the shift of power, and discourse, away from the Mediterranean to central Europe. To speak of Roman versus Early Medieval 'Germanic' dietary differences it simply to speak of the geographic divide between the Mediterranean and central Europe. Yet the potential changes in consumption patterns are supported by some archaeological evidence from central/southern Italy. At San Vincenzo al Volturno there is evidence for a reliance on animal products in the early Medieval period, and for a collapse of trade (Hodges, 1997).

The second argument uses an alternative interpretation of dietary changes in this period downplays the differences between Roman and early Medieval subsistence practices. This is partly related to the broad geographic differences between continental and Mediterranean zones, as well as smaller-scale interregional differences. These would have resulted in local agricultural and dietary adaptations regardless of political circumstances. This hypothesis assumes a more restricted view of the Roman economy, emphasizing that self-sufficiency would have been far more prevalent than suggested by literary references. When one includes the view of the persistence of the Roman economic patterns until the 6th century, and the origins of the revitalized European economy in the 8th century, the actual Early Medieval economic depression may have been restricted and difficult to distinguish from the Roman period.

The subsequent chapters will discuss how stable isotope analysis has been used in this study to examine the dietary impact of these two competing hypotheses of economic change. Economic forces were not the only ones responsible for dietary differences. The influences of social status, including age and sex, as well as religious and cultural factors would have affected diet. The increasing prominence of Christian fasting practices may have counteracted the meat-eating ideology of the early Medieval period. These will all be considered in the reconstruction of Roman and Medieval diet that follows.

3

Stable Isotope Analysis in Archaeology

For over 30 years, stable isotope analysis has been used in archaeology to examine ancient diet. This chapter explores the mechanisms by which stable carbon and nitrogen isotopes move through the ecosystem and eventually become incorporated in human bone. The second half of this chapter examines the potential uncertainties and problems with stable isotope analysis when used for palaeodietary reconstructions.

3.1 Stable carbon isotope ratios

In dietary reconstructions, differences in carbon isotope ratios can be used to discriminate between different types of plant resources, as well as between some terrestrial and marine resources. Isotopic offsets are expressed as parts per thousand (per mille) relative to a standard using delta notation according to the following equation:

$$\delta^{13}\mathrm{C} = [(R_{sample}/R_{standard}) - 1] \times 1000(‰)$$

Carbon isotope ratios are measured relative to the PeeDee Belemnite, which is relatively rich in ^{13}C, making most δ^{13}C values measured in plants negative.

Prior to the industrial revolution, atmospheric δ^{13}C values were higher than they are today. In the last several hundred years, the increased burning of fossil fuels has resulted in ^{13}C-rich carbon being added to the atmosphere, lowering modern atmospheric δ^{13}C values compared to ancient ones by about 1.5‰ (Francey et al., 2002; Friedli et al., 1986; Keeling et al., 2001; Langenfelds et al., 2002; Verburg, 2007).

3.1.1 C3 and C4 plants

Fractionation of carbon in the ecosystem begins with the photosynthesis of plants, which combine atmospheric CO_2 with water to produce sugars. As atmospheric CO_2 ($\delta^{13}C = -7$ to -8‰) diffuses into the tissue of the plant, the lighter isotope diffuses more quickly. The enzymes that assist the plant in undergoing photosynthesis also favour ^{12}C over ^{13}C, meaning that plant carbon is isotopically lighter than the atmospheric CO_2 carbon with which it was created (Farquhar et al., 1989).

The amount of fractionation that takes place depends on the type of photosynthetic pathway employed by the species of plant. Most plants use the Calvin-Benson method, and they are called C3 plants because the first product of the photosynthesis reaction is a molecule containing three carbon atoms. This process heavily favours the lighter ^{12}C atoms, and results in large offsets, averaging -26‰ with a usual range of -22 to -33‰ (Bender, 1971). C3 plants include most species that are found in temperate environments, including trees, shrubs, and several important food plants such as wheat, barley, oats, rye and rice, as well as fruits and vegetables.

Some plants use the Hatch-Slack pathway. These are C4 plants which use a four-carbon molecule to fix carbon. C4 plants are mostly tropical grasses, but include some important domesticates such as maize, sugarcane, sorghum and millet (Farquhar et al., 1989; Osborne and Beerling, 2006). C4 photosynthesis makes more efficient use of atmospheric CO_2, resulting in a smaller difference between atmospheric δ^{13}C and plant δ^{13}C, which have values around -12‰.

A third category of plants is able to switch between the C3 and C4 pathway depending on environmental conditions with a mechanism called Crassulacean Acid Metabolism (CAM). This method of photosynthesis is commonly found in succulents, such as cacti, because it efficiently conserves water in arid environments. Fortunately, succulents do not play an important role in human diet in Roman and Medieval Europe, and the complication of CAM plants can be discounted. Although C3 and C4 plants are easily distinguished based on their δ^{13}C values, there is a large amount of variation, both within and between species. Factors which can affect δ^{13}C include the amount of light, water, salinity and pollution, as well as the 'canopy effect' of forests (Farquhar et al., 1989; see 3.4).

When animals consume plants the carbon isotopic ratios of their diet are incorporated with a slight offset (due to metabolic processes) into their tissues, including bone collagen. For herbivores, the diet-collagen δ^{13}C increases have been measured in animal feeding experiments in rats ($2-4$‰; DeNiro and Epstein, 1978), while Hare et al. (1991) examined pigs, whose digestive systems are similar to humans. They found a diet to collagen δ^{13}C increase of +3.2 (C3 diet) and +1.4 (C4 diet), based ten pigs for each dietary category. A smaller trophic level shift persists through the ecosystem for carnivorous diets. Post (2002) reports an average δ^{13}C trophic level shift of $+0.4 \pm 1.3$‰ in ecological literature. To avoid problems with estimating food-diet δ^{13}C differences in making dietary reconstructions, this study uses comparisons of human collagen δ^{13}C on different diets. A small correction factor must be applied to human collagen δ^{13}C to account for possible trophic level differences. Bocherens and Drucker (2003) measured a δ^{13}C trophic level enrichment of +1.0 and +1.1 for wild wolf and lynx. Human infants who are being breastfed also show a 1‰ δ^{13}C increase in hair and fingernails (Fuller et al., 2004, 2006a), and in rib collagen (Nitsch et al., 2011).

Using δ^{13}C it is possible to distinguish between diets based on C3 or C4 resources (see Figure 3.1). It has been successfully applied to prehistoric North

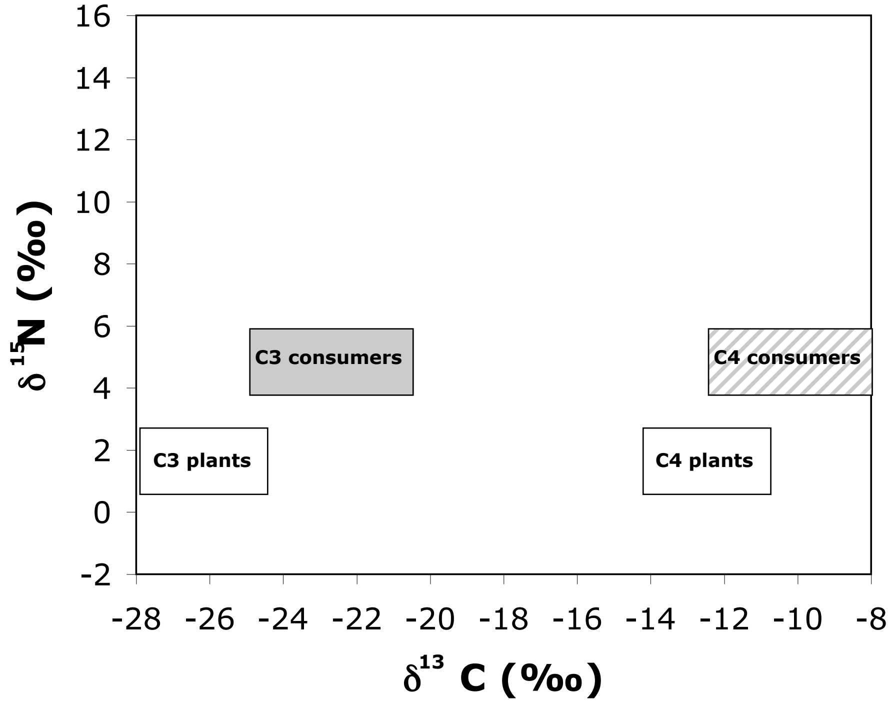

Figure 3.1: *Illustration of isotopic differences between C3 and C4 plants and their consumers.*

America, where δ^{13}C ratios track the increasing contribution of C4 domesticated maize into a predominantly C3 environment (e.g. Vogel and van der Merwe, 1977) and on a similar basis has also been used to examine the origins of millet agriculture in China (Hu et al., 2008).

3.1.2 Carbon in marine environments

The isotopic system is more complex for oceanic carbon. Carbon in the ocean is made up of dissolved carbon dioxide, bicarbonate and carbonate ions, each of which undergo isotopic fractionation to different degrees. Experimental evidence has shown that the variation in plankton δ^{13}C values is due to variations in the temperature and pH of seawater, which together control the amount of carbon dioxide available for the plankton to photosynthesize, which in turn affects the degree of fractionation that takes place (Deuser et al., 1968). Phytoplankton discriminate against ^{13}C to the same extent as C3 plants, so the photosynthesis at the bottom of the marine food chain results in a similar −19‰ offset from the source carbon. Since the bicarbonate dissolved in seawater is 7‰ higher than atmospheric CO_2 (Craig, 1953), the baseline of the marine food chain for carbon isotope ratios is approximately 7‰ higher than the terrestrial food chain.

This difference was first used to infer marine consumption by Tauber (1981) who examined δ^{13}C values for radiocarbon-dated samples from Mesolithic and Neolithic Denmark. He noted that the coastal populations from the Mesolithic period had significantly higher δ^{13}C values, which was likely due to marine protein consumption. Chisholm et al. (1982) was the first study to test whether the 7‰ difference between terrestrial CO_2 and oceanic bicarbonate that had been noted by Craig (1953) would carry through the food chain to human bone collagen. This study found an offset of 7.9‰ between terrestrial and marine mammals, and on this basis concluded that the coastal humans from British Columbia who had significantly higher δ^{13}C ratios than a comparative sample from the Ottawa Valley must have consumed more marine protein.

3.2 Stable Nitrogen Isotope Ratios

Nitrogen in the ecosystem is ultimately derived from atmospheric N_2 which becomes incorporated into soils through nitrogen-fixing bacteria. These plants exhibit elevated δ^{15}N ratios compared to the soils in which they grow because denitrification processes in the soil tend to increase the amount of ^{15}N present, and plant tissues preferentially incorporate ^{15}N (Heaton, 1986; Shearer and Kohl, 1986). These plants can have variable δ^{15}N ratios (between 2 and 10‰) due to the variety of nitrogen sources in the soil, including NH_4, NO_2, NO_3 and various amino acids (Schoeninger and DeNiro, 1984). Legumes fix nitrogen directly from the atmosphere and have δ^{15}N values closer to atmospheric values, and so are about 2‰ lower in δ^{15}N compared to non-leguminous plants (Virginia and Delwiche, 1982).

In animals most of the nitrogen consumed is used to form amino acids, which are combined to make proteins. When protein is consumed it is separated into its constituent amino acids in the stomach. These amino acids are used for protein synthesis. While some are incorporated directly into proteins, others are ultimately broken down through deamination, with most of the nitrogen being converted into urea or ammonia which is excreted (Eastwood, 2003). One of the largest sources of nitrogen fractionation is due to the deamination and transamination process, meaning that metabolized amino acids become enriched in ^{15}N during anabolism, resulting in the observed ^{15}N depletion of excreted nitrogen in urea (Macko et al., 1987). The heavier isotope is preferentially used for protein synthesis, while isotopically light nitrogen is excreted (Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984). The ^{15}N-rich proteins which make up an organism's tissues have higher δ^{15}N than its diet. This has been confirmed through controlled feeding experiments in animals. Early studies showed that animal muscle tissue was $1-3‰$ higher than diet (Steele and Daniel, 1978) and a similar diet to collagen δ^{15}N enrichment of (+1.3 – 3.4) was found in mice (DeNiro and Epstein, 1981).

3.2.1 Trophic levels

The difference in δ^{15}N between an organism's diet and tissues means that the relationship between consumer and food can be tracked through δ^{15}N. Herbivores will have δ^{15}N ratios higher than the plants they consume, and the carnivores that consume them will be higher still. Omnivorous species, including humans, will have δ^{15}N ratios between those of herbivores and carnivores. Humans on vegetarian diets, if they still obtain animal protein from milk and eggs, will have omnivorous δ^{15}N, but vegans consuming no animal protein will have δ^{15}N similar to herbivores (O'Connell and Hedges, 1999a). Nitrogen stable isotope ratios cannot distinguish between the consumption of animal meat and the consumption of secondary animal products (i.e. milk, cheese).

The difference in δ^{15}N between trophic levels can vary widely depending on the species. The uncertainty in ^{15}N trophic level enrichment in humans makes a large difference in constructing dietary models (Hedges and Reynard, 2007). This uncertainty is further compounded by intra-species and intra-trophic level variation. Controlled feeding experiments are the only accurate way to measure this value, but it is difficult to do so in larger species, especially humans. Instead it can be indirectly measured using predator-prey relationships. The ecological literature on δ^{15}N trophic level increase (Δ^{15}N) has been reviewed by McCutchan et al. (2003), Post (2002), Robbins et al. (2005) and Vanderklift and Ponsard (2003). In general these studies suggest an average $\Delta^{15}\mathrm{N}_{\text{diet-body}}$ of $+2.3 - 3.0$‰ across a range of invertebrates, marine species, and small and large mammals.

McCutchan et al. (2003) noted that there were significant differences in the Δ^{15}N spacing for two different types of high protein diets: those species that ate only invertebrates ($\Delta^{15}\mathrm{N}_{\text{diet-body}} = +1.4 \pm 0.21$‰) compared to all other high protein diets ($\Delta^{15}\mathrm{N}_{\text{diet-body}} = +3.3 \pm 0.26$‰). They had expected that the trophic level shift for δ^{15}N would be greatest for those animals with the highest amounts of nitrogen in their diets (those consuming the largest amounts of protein) since these animals have the highest rates of nitrogen excretion relative to assimilation. However, they found no difference in the trophic level $\Delta^{15}\mathrm{N}_{\text{diet-body}}$ increase between carnivores and herbivores. The complication of protein quality/quantity is discussed in 3.6 below. Robbins et al. (2005) reviewed studies on mammals and birds and found a wider range of $\Delta^{15}\mathrm{N}_{\text{diet-body}}$, from $1.4 - 5.8$‰, although Hedges and Reynard (2007) point out that the outliers could be due to interference from animals who were not weaned, or due to unusual diets.

Controlled feeding experiments may provide a more accurate assessment. For pigs, two separate experiments have measured $\Delta^{15}\mathrm{N}_{\text{diet-collagen}}$ of $2.2-2.3$‰ (Hare et al., 1991) and $0.5 - 6.1$‰ (Howland et al., 2003). The difference between the two pig studies suggests that there are a number of unknown factors that can affect trophic level increase in δ^{15}N.

The trophic level δ^{15}N increase can be measured in humans, using $\Delta^{15}\mathrm{N}_{\text{diet-hair}}$ of living individuals. Yoshinaga et al. (1996) found a range of $5.0-6.9$‰ based on a calculated, rather than measured, diet. A difference of 4.1 ± 0.7 was found for modern Fijians, again based on calculated dietary values (Hedges et al., 2009). If we accept a range in human $\Delta^{15}\mathrm{N}_{\text{diet-hair}}$ of $4-5$‰ (Hedges and Reynard, 2007), the corresponding $\Delta^{15}\mathrm{N}_{\text{diet-collagen}}$ for humans would be $5-6$‰, since there is an offset between δ^{15}N of human keratin and human collagen of about 1‰ (O'Connell and Hedges, 1999b). Understanding the expected $\Delta^{15}\mathrm{N}_{\text{diet-collagen}}$ increase is essential for attempting to reconstruct the amount of animal protein in the diet. Humans with δ^{15}N identical to herbivorous animals likely (but not necessarily) consumed a similar diet. Humans with δ^{15}N equal to the herbivore δ^{15}N + one trophic level increase would be assumed to be entirely carnivorous. Most studies assume a trophic level increase of between 3 and 5‰ but Hedges and Reynard (2007) have shown that this does not always lead to plausible dietary reconstructions in archaeological populations. A number of sites summarized by Hedges and Reynard report human-fauna δ^{15}N differences of 4‰ or greater, leading to the interpretation that humans consumed an unrealistically large amount of animal protein. To overcome this problem they present four alternative models that can be used to take some of the uncertainty in reconstructing trophic level relationships into account. These models will be applied to the data from Roman and Medieval Europe in Chapter 7. One of the potential sources of error that Hedges and Reynard (2007) did not consider was the effect of aquatic and marine foods on δ^{15}N.

3.2.2 Nitrogen in Marine Environments

Similar to terrestrial environments, nitrogen fixation in the sea preferences ^{14}N, making isotope ratios lighter, and leaving ^{15}N behind. However, baseline

δ^{15}N values are higher in the sea due to isotopically heavier nitrogen entering the ocean from terrestrial runoff, making marine plant δ^{15}N values higher than terrestrial ones (Wada et al., 1975). Marine ecosystems have much more complicated trophic level relationships than terrestrial ecosystems, and can accordingly have a much wider range of δ^{15}N. Humans consuming high trophic level marine foods can have collagen δ^{15}N values as high was 20‰ (Schoeninger and DeNiro, 1983), which is similar to reported δ^{15}N values of top level marine carnivores (Richards and Hedges, 1999). Marine foods can also include a number of low trophic level foods, such as small fish and shellfish, which would have high δ^{13}C values due to the marine carbon (see 3.1.2 above) but low δ^{15}N. On land, terrestrial plant δ^{15}N can be affected by nitrates from sea spray. Coastal plants have higher δ^{15}N than their inland counterparts. This is due to two factors: first, oceanic nitrate has a higher δ^{15}N ($+5 - 10$‰) than terrestrial nitrate (Virginia and Delwiche, 1982); and second, ^{15}N enrichment in the soil occurs as a result of increased salinity in proximity to the sea (Heaton, 1987).

3.2.3 Freshwater fish

Freshwater food chains, like marine food chains, are longer than terrestrial ones, although modern riverine food chains tend to be shorter than food chains in lakes and marine environments (Vander Zanden and Fetzer, 2007). Freshwater fish can have much higher δ^{15}N values than terrestrial animals, but still lower than high trophic level marine species (Schoeninger and DeNiro, 1984). France (1994) confirmed that freshwater fish tend to be about 5‰ lower in δ^{15}N than marine fish, but isotopic ratios can be highly variable.

Freshwater carbon is not subject to the same fractionation effects as oceanic carbon, and δ^{13}C values for freshwater fish appear terrestrial, although can vary widely. Reported values of freshwater fish can range between a δ^{13}C of -32.2 to -19.8‰ and a δ^{15}N of 6.5 to 14.9‰ (Bocherens and Drucker, 2003; Dufour et al., 1999). This variability is due to the different δ^{13}C of dissolved bicarbonate, which is in equilibrium with different sources of CO_2. If it is in equilibrium with atmospheric CO_2, which is more common in large lakes, it will have a δ^{13}C value close to 0‰. If it is in equilibrium with CO_2 derived from degraded terrestrial detritus or other organic material it will have a more negative δ^{13}C (Dufour et al., 1999). Estuaries also present problems for stable isotope studies. Estuarine environments are complex, since they have input from both freshwater and marine systems, and tend to show intermediate δ^{13}C and δ^{15}N (Peterson and Howarth, 1987; Richards and Schulting, 2006; Vizzini and Mazzola, 2009). Dufour et al. (1999) recommend studying archaeological fish to determine a baseline, or their modern equivalents as a second best alternative. In the Roman and Medieval period, fish pond aquaculture could result in a very unique isotopic system. Müldner and Richards (2005) found one pike specimen from the 14th-15th century deposit at the Dominican Priory at Beverley in East Yorkshire with a δ^{15}N value of 23.4‰ which is much higher than any previously reported specimen from a lake, and suggests that it was raised in an unusual, separate ecosystem, such as a fish pond.

Individuals consuming large amounts of freshwater resources would have elevated δ^{15}N. Cook et al. (2001) compared human isotopic values to contemporary ungulates at the Iron Gates Gorge and found a difference of +2.3 in δ^{13}C and +8.6 in δ^{15}N which suggested freshwater resources with high δ^{15}N had been consumed by the humans. However, smaller amounts of freshwater fish which do not obviously affect δ^{15}N are not easy to detect, and their consumption can confound estimates of animal protein consumption based on δ^{15}N values (Hedges and Reynard, 2007). Freshwater fish is normally only considered in palaeodietary studies where there is good supporting evidence, from radiocarbon offsets or zooarchaeology, or from anomalously high δ^{15}N values (e.g. Rutgers et al., 2009).

3.2.4 Altered metabolic states and δ^{15}N

When the body is in a steady metabolic state, there is an equilibrium between the macronutrients produced and consumed. During growth, however, additional protein is required to synthesize new tissues, which creates a deficit in nitrogen. The extra nitrogen is achieved through the assimilation of large amounts of amino acids (Schwarcz, 2002), in what is called positive nitrogen balance. More nitrogen is used than is excreted. The synthesis of new tissue (anabolism) is more prevalent than catabolism and tissue replacement. The extra protein requirements will often be met by non-essential amino acids being routed directly from food.[1] This increase in direct synthesis and decrease in transamination reactions means that the overall δ^{15}N of newly synthesized tissues will be lower during states of growth (Fuller et al., 2004, 2005; Ponsard and Averbuch, 1999). In young animals and humans, some of these non-essential amino acids must be obtained from food sources because the rate at which they are required is greater than what the body can itself produce, even though during a steady state they area easily produced (Schwarcz, 2002). During states of growth there is likely less fractionation of δ^{13}C between diet and collagen due to this increase in direct collagen routing (Hare et al., 1991).

Pregnancy is also a state of growth, characterized by increased protein synthesis and decreased nitrogen excretion (Thompson and Halliday, 1992) which could result in low δ^{15}N in body tissues. Lower δ^{15}N in pregnant women has been found in hair and fingernail samples from modern populations. Two studies of pregnant women observed depletions in ^{15}N that began during gestation and increased to a maximum of between 0.3 and 1.1‰ lower than pre-pregnancy levels, 10-20 weeks after the infant was born (Fuller et al., 2004, 2006b). In archaeological contexts, the long turnover period of bone collagen (see 3.5.1 below) means that temporary periods of altered metabolic states, such as pregnancy, are unlikely to have an overall effect. A comparison of rib collagen δ^{15}N for women of known parity history found no significant differences due to the effect of pregnancy, which was explained by models of collagen turnover rates (Nitsch et al., 2010).

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[1] I use the more familiar terms 'non-essential' and 'essential' amino acids to refer to the more technical terms 'dispensable' and 'indispensable' amino acids

Modelling of human infant growth patterns suggests that a small decrease in δ^{15}N (0.25‰) is possible in weaned children compared to adult diet because of the effect of growth (Millard, 2000). Further modelling of nitrogen balance during growth of animals (Ponsard and Averbuch, 1999) and tests of collagen δ^{15}N values on bone (Waters-Rist and Katzenberg, 2010) suggest that the effect of growth on bone collagen δ^{15}N would be minimal. Waters-Rist and Katzenberg (2010) found no difference in δ^{15}N between samples taken from bone undergoing growth and samples from bone that had already ceased growing. It is likely that the effect of collagen turnover masked any alteration in δ^{15}N due to growth, similar to the models of collagen turnover for pregnancy discussed by Nitsch et al. (2010).

At birth an infant's δ^{15}N is identical to the maternal value, but quickly increases $3 - 5$‰ above this baseline through the consumption of breast milk, since the infant is feeding at a trophic level higher than the mother. Prior to weaning infants have δ^{15}N values obviously higher than the adult population (Fogel et al., 1989; Fuller et al., 2004, 2006b). A number of archaeological studies have used changes in δ^{15}N to track the weaning schedule in ancient populations, both using infant bone collagen (e. g. Clayton et al., 2006; Dupras et al., 2001; Fuller et al., 2006b; Jay et al., 2008; Katzenberg et al., 1993; Prowse et al., 2008; Schurr, 1997; Schurr and Powell, 2005) and using adult dentine, which preserves the signal from childhood (e.g. Dupras and Tocheri, 2007; Fuller et al., 2003).

Starvation is the opposite of growth, since the amount of nitrogen excreted is less than the amount of nitrogen consumed. In the absence of adequate external sources of protein, the body must recycle nitrogen from the breakdown of its own amino acids. By continuing to preferentially excrete isotopically light nitrogen, the body's nitrogen will become increasingly enriched in ^{15}N (Fuller et al., 2005; Hobson et al., 1993). In other words, starvation increases the body's δ^{15}N value since the rate of nitrogen excretion is essentially infinitely high relative to the rate of nitrogen incorporation (McCutchan et al., 2003). Starving animals show an increase in $\delta^{15}N$ (Hobson et al., 1993; Oelbermann and Scheu, 2002; Voigt and Matt, 2004). In Japanese quail under nutritional stress, collagen $\delta^{15}N$ was 1‰ higher compared to non-stressed individuals (Hobson et al., 1993). Humans undergoing nutritional stress also exhibit higher $\delta^{15}N$ in hair, while $\delta^{13}C$ remains unchanged (Fuller et al., 2005). Illness and pathology can also affect $\delta^{15}N$ if pathological areas of bone are analysed (Katzenberg and Lovell, 1999; White and Armelagos, 1997), although this effect can be avoided by omitting samples that are obviously pathological.

3.3 Anthropogenic effects

Manuring may introduce ^{15}N-rich compounds to soils, which can be taken up by plants, a potential source of variation which has been problematic since the earliest isotopic studies (DeNiro and Epstein, 1981). Manure contains the isotopically light nitrogen-bearing compounds which are excreted by the animal's body, but the more volatile ^{14}N molecules of ammonia are lost, leaving behind ^{15}N rich ammonium. This ammonium is converted into ^{15}N-rich nitrate, which is soluble in water and incorporated into plant tissue (Heaton, 1986). Manuring is known to increase soil $\delta^{15}N$ and the heavier isotope of nitrogen derived from manure is known to be incorporated into plants that grow on these soils (Bol et al., 2005; Simpson et al., 1999). Initial results showed that wheat grown on manured soils was $4-5$‰ higher in $\delta^{15}N$ than wheat grown in unmanured soils (Bogaard et al., 2007). Further experiments showed that unmanured wheat in Europe typically has $\delta^{15}N$ values of less than 2.5‰, heavily manured wheat has $\delta^{15}N$ greater than 6‰, with intermediate manuring practices measuring between these two values (Fraser et al., 2011). This study also demonstrated the long-term effects of manure on $\delta^{15}N$ in soil and plants, since the long-term field experiments showed a stronger manuring effect than the short-term field experiments. Their study also noted the retention of high $\delta^{15}N$ in soils for years after the end of a manuring regime. An increasing N load due to fertilizer run-off in modern ecosystems has been shown to increase d15N in aquatic ecosystems as well (Cole et al., 2004), with effects throughout the food-web (Cabana and Rasmussen, 1996).

The effect of manuring has implications for palaeodietary reconstruction. Differences in manuring practices can result in an apparent trophic level shift in nitrogen. High human δ^{15}N values on their own do not necessarily indicate a reliance on significant quantities of animal products. Differences between human and animal δ^{15}N have been used to reconstruct this relationship, but such a reconstruction rests on the assumption that humans and animals consume plants of the same δ^{15}N (Hedges and Reynard, 2007). Manure was in limited supply in ancient farms, and was likely used selectively (see Chapter 2), and so there is a potential for crops and fodder to have different δ^{15}N ratios. One of the models for dietary reconstruction developed by Hedges and Reynard (2007) includes a correction factor for this potential offset between animal and human δ^{15}N baselines, which will be incorporated in the analysis presented here.

3.4 Geography and Climate

Carbon and nitrogen isotopic ratios in plants vary according to geographic and climatic factors, which were reviewed most recently by van Klinken et al. (2002). Climatic effects on δ^{13}C include temperature and air pressure, which can be observed in differences due to latitude and altitude (Körner et al., 1991). Van Klinken et al., (2002) identify changes in δ^{13}C on the order of 2 to 4‰ across the European continent related to both continentality (E-W) and temperature (N-S). More localized differences can occur due to small differences in soil, water availability and light intensity (Heaton, 1999). A review by Heaton (1999) found that intra-population variation in δ^{13}C could be ±1.5‰ with additional variations of up to 1.5‰ depending on the part of the plant sampled. Different species in the same environment could vary up to 4‰.

Wood charcoal δ^{13}C values from across Europe were found to correlate with mean July daily maximum temperature (van Klinken et al., 1994). On the basis of this correlation, a regression equation was calculated, to apply a correction factor for wood relative to an assumed standard value of -26‰.

$$y = -30.202 + 0.214x$$

where y is the corrected δ^{13}C value (‰) and x is the average July daily maximum temperature in °C (van Klinken et al., 1994). This is similar to the increase in δ^{13}C of 0.3‰ per °C suggested by (Heaton, 1999). Heaton also suggested additional corrections of -0.1‰/% relative humidity in mid-summer, and +1‰ / 1000m altitude.

Nitrogen isotopic ratios are sensitive to local soil conditions. Drought can exert pressure on the nitrogen excretion system, and has the potential to cause differences in δ^{15}N. Soil in drought conditions shows increased δ^{15}N because of the reduction in the fixation of N_2 by nitrogen fixing bacteria and due to the increasing volatilization of ^{14}N ammonia. Plant δ^{15}N values are known to increase with decreasing rainfall, with decreases of $0.3 - 0.4$‰ for every additional 100mm of rain per year (Heaton, 1987). The effect on herbivores is even greater, with increases of $1.1 - 1.3$‰ for every 100mm less of rainfall (Heaton, 1986, 1987). Variations in δ^{15}N of $10 - 11$‰ have been observed within a single trophic level, depending on the species and habitat (Ambrose, 1991). In practice, however, Fraser et al. (2011) found that the manuring signal in δ^{15}N masked any effect due to rainfall and climate in experimentally grown crops, suggesting that manuring status may be a more significant factor in crop stable isotope ratios than overall climatic conditions.

Drought can also affect nitrogen isotopic ratios in animals directly. The major drought-related factor affecting mammal δ^{15}N appears to be the degree to which the animal is able to concentrate urea in response to heat and water stress (Ambrose, 1991). Since urea is ^{15}N-depleted (Steele and Daniel, 1978) animals under heat stress will excrete more ^{15}N-depleted urea, leaving ^{15}N-rich nitrogen for the synthesis of new protein. Since the lighter nitrogen isotope tends to be donated and excreted, and since drought conditions are associated with increased nitrogen excretion, δ^{15}N values in the organism become higher during water stress (Hare et al., 1991). In general, continental European climate is not sufficiently arid or warm to influence δ^{15}N based on observed data (van Klinken et al., 2002). However, for the more arid regions of the Mediterranean included in the meta-analysis (Chapter 6) such effects will be considered.

European δ^{15}N values may also be influenced by other local conditions. Salinity has been shown to increase δ^{15}N ratios in plants and soils, especially in salt-marshes (Britton et al., 2008). Plants growing near the sea (Virginia and Delwiche, 1982) or in salt marshes (Cloern et al., 2002) have higher δ^{15}N, likely due to the combined effect of nitrates from sea-spray and the effect of salinity on denitrification (Ambrose, 1991; Heaton, 1987). Britton et al. (2008) found an average difference of 2.7‰ in δ^{15}N between herbivores from salt-marsh sites and those from other locations.

3.5 Bone Chemistry: collagen

Bone is made up of two components: an organic component, consisting largely of the protein collagen, and an inorganic matrix of hydroxyapatite crystals. Like all proteins, collagen is composed of different amino acids in varying proportions. It is formed from both non-essential amino acids, which the body synthesizes on its own, and the essential amino acids which are obtained from food.

The collagen molecule is composed of three polypeptide chains, called alpha chains, which are each about 1000 amino acids long. A single molecule of collagen weighs between 95 and 102 kD (where 1kD = 1000 amu, and 1 amu is defined as 1/12 the mass of a carbon-12 atom). Collagen makes up nearly 30% of living bone by weight and so can be extracted in large quantities. Its triple-helix structure, embedded within the hydroxyapatite crystals of bone, make it extremely resistant to enzyme hydrolysis, and means that its chemical and isotopic composition can be assumed to reflect its biogenic origins. Early experiments indicated that amino acid profiles of collagen remain consistent until samples are very degraded and have very low yields of between 0.5 and 1% weight (Beeley and Lunt, 1980). More recent work on artificially and archaeologically degraded collagen has further demonstrated that the measured properties of collagen, including δ^{13}C, δ^{15}N and C/N ratio, remain consistent until collagen yields fall below this 1% weight threshold (Dobberstein et al., 2009).

3.5.1 Collagen Turnover

Over time, the body replaces old collagen with new collagen, but the exact turnover rate is difficult to measure experimentally and varies depending on the bone sampled. Turnover is usually expressed as the amount of new tissue replacing old tissue compared to a total, over a period of time, often in percent per year (Parfitt, 2002). In the cortical bone of the femur, up to 50% of the collagen in later adulthood may be the remains of collagen synthesized during the body's last major growth spurt in adolescence (Hedges et al., 2007). For the cortical bone of the sixth human rib, turnover rates varied depending on the age of the individual, from as high as 84% per year in the first year of life, to an average of 4% per year for adults over the age of 50 years (Frost, 1969). Ribs are mostly made up of spongy cancellous bone, which is thought to turn over more quickly (Sealy et al., 1995) but the turnover rate actually varies, with the inner surface of the cortical bone having the highest turnover rate, and the centre of the cancellous bone having the lowest turnover rate (Parfitt, 2002). During periods of rapid bone growth, such as childhood or wound-healing, tissue turnover rates will be much higher, and so incorporate changes in diet more quickly (Bollen and Eyre, 1994; Frost, 1969). Some types of disease, such as osteogenesis imperfecta, can also affect bone turnover rates, with decreased collagen synthesis and increased bone remodelling (Brenner et al., 1994).

3.5.2 Isotopic Routing

The only significant dietary source of nitrogen is protein, so the nitrogen which makes up collagen must be derived from the protein component of the diet. Carbon, however, is also present in lipids and carbohydrates, meaning that collagen carbon could potentially be derived from a mixture of carbon from all dietary macronutrients. Most of the non-essential amino acids, representing 78% of the carbon atoms in collagen, can be synthesized by the body from the metabolism of sugars and fats, meaning that the δ^{13}C ratio of these amino acids could reflect the δ^{13}C ratio of the total diet (O'Connell and Hedges, 2001; Schwarcz, 2002). This 'scrambled egg' model of carbon routing to collagen was assumed to be the case for early isotopic studies (Burleigh and Brothwell, 1978; DeNiro and Epstein, 1978; Schoeninger et al., 1989; Schwarcz, 2002).

The opposing theory is the direct routing hypothesis, which suggests that most of collagen carbon is derived directly from the breakdown of the amino acids found in protein, and that collagen amino acids are synthesized only from protein-derived carbon. Essential amino acids contribute 22% of the carbon in collagen, and this carbon must originate directly from the amino acids in the protein component of the diet. For the remaining 78% of collagen carbon atoms from non-essential amino acids, it was necessary to determine whether the body would prefer to directly incorporate the ingested amino acids for protein synthesis, or whether it would prefer to synthesize them endogenously. This was tested using feeding experiments where the isotopic composition of the different dietary macronutrients could be controlled so that the protein, carbohydrate and lipid components of the diet were distinguishable (Ambrose and Norr, 1993; Tieszen and Fagre, 1993). These experiments demonstrated the clear preference for the inclusion of pre-formed exogenous non-essential amino acids, rather than *de novo* synthesis, with up to 90% of carbon in collagen deriving from the protein content of the diet. Using pre-formed amino acids is more energy efficient. In addition, the internal synthesis of amino acids is inhibited by high concentrations of the product amino acid in the intracellular fluid. When a non-essential amino acid is present in adequate concentrations in an animal's diet, it will be incorporated directly from the diet into the consumer's tissues (Schwarcz, 2002).

The reverse may occur when there are not adequate amounts of non-essential amino acids in the diet. Later studies found that some collagen amino acids can be synthesized from carbohydrates and lipids depending on the quantity and quality of the protein in the diet. Jim et al. (2006) found that a minimum of 50% of collagen carbon must be derived from dietary protein, and that the amount of carbon derived from protein increases as the amount of protein in the diet increases. In this situation the carbon content would mostly reflect the protein contribution of the diet. However, this study also found that even in diets where there is an excess of protein, some of the carbon will still be derived from non-protein sources.

The experimental evidence suggests that at least 50% and as much as 90% of the carbon in collagen is derived from the protein content of the diet. This is a large degree of uncertainty. In addition, the experimental data derives from rats and pigs, and the degree to which these effects would occur in humans is unknown. Schwarcz (2002) argues that the remainder of the carbon in collagen likely reflects the carbohydrate component of the diet, rather than the carbohydrate + lipid component. This is because carbon from lipids is preferentially excluded from amino acid synthesis. Fatty acids cannot be converted into glucose, and glucose-glycolysis is the preferred pathway for the synthesis of many amino acids, such as alanine and glycine. This means that alanine and glycine are more likely to incorporate carbon derived from the carbohydrate content of the diet, rather than the lipid component (Schwarcz, 2002). Animal feeding experiments have shown that total collagen δ^{13}C values are extremely insensitive to changes in the dietary lipid δ^{13}C (Tieszen and Fagre, 1993). The degree to which collagen carbon derives from protein versus carbohydrate sources is potentially significant, since the δ^{13}C composition of the carbohydrate sources of the diet can be dramatically different from the δ^{13}C composition of the protein sources of the diet. The consumption of marine fish, which contain negligible amounts of carbohydrate, could be masked if carbon from carbohydrates is included in collagen.

3.6 Effect of protein quality and quantity

The quantity and quality of protein in the diet can have a significant effect on carbon isotopic ratios. It is clear that an almost total routing of protein carbon to collagen does not always occur. The extremely high (> -10‰) δ^{13}C values among some maize agriculturalists are consistent with a large amount of C4 plants in the diet. However, assuming a total routing of C4-plant derived carbon directly to collagen produces unrealistically high contributions of maize to the diet, over 70%, and in some cases over 100% (Schwarcz, 2002). To account for this, Schwarcz pointed out the work of Krueger and Sullivan (1984) illustrating that the endogenous synthesis of non-essential amino acids would be increased in individuals who have low protein intake. In this situation low-protein diets would result in carbon from both carbohydrates and protein being used to synthesize new amino acids in the body, and the δ^{13}C value of collagen would reflect a greater proportion of the carbohydrate δ^{13}C than under higher levels of protein intake.

There is experimental evidence for an increase in endogenous non-essential amino acid synthesis under extremely low protein regimes in humans (Jackson, 1995; Tanaka et al., 1980). The increase in endogenous non-essential amino acid synthesis is believed to be triggered by an overall low amount of dietary nitrogen (Jackson, 1995), but there is no experimental data on humans or comparable mammals to suggest how low protein intake needs to be before this synthesis is triggered. This is because of the complex inter-individual and intra-individual variations in nitrogen metabolism that make nitrogen balance difficult to measure (WHO Technical Report Series, 2007). The recommended intake of 0.83g protein/kg body weight per day would satisfy the requirements for most (97.5%) healthy adults, but a meta-analysis of previous literature shows that nitrogen balance can be met with as little as 0.31g/kg /day in some individuals, while for others, protein intake as high as 0.94g/kg/day was not enough to sustain nitrogen balance (WHO Technical Report Series, 2007, 106).

Some indication of the threshold at which direct routing of protein carbon to collagen becomes dominant can be gained from animal feeding experiments. Ambrose and Norr (1993) showed that collagen from low-protein diets contained more carbon from the lipid and carbohydrate component of the diet, while collagen on high protein diets was close to the isotopic value of the protein. When the protein content of the diet was 5%, protein contributed $42-51\%$ of the total carbon in collagen. At 20% protein, carbon from protein contributed $66-71\%$ carbon; when the diet contained 70% protein, carbon from protein made up $88-95\%$ of the carbon atoms in collagen. Analysis of individual amino acid δ^{13}C of collagen from rats in a different controlled feeding experiment confirmed that the non-essential amino acids are more likely to contain carbon reflecting the total dietary carbon δ^{13}C (Jim et al., 2006). In this study, models of the relationship between collagen and dietary amino acid δ^{13}C suggested that the threshold for the routing of dietary protein to collagen was would be reached when the diet contained between 5 and 12% protein by weight, but this threshold has not been measured experimentally. It is therefore possible that carbon from non-protein source could make a significant ($> 10\%$) contribution to collagen carbon.

Based on current experimental data there is no simple way to determine the effect of low-protein diets and differential carbon routing on human bone collagen δ^{13}C. I have made a simple calculation to illustrate the potential effect of differences in carbon routing on δ^{13}C. I calculated the distance between two extreme dietary endpoints, one in which the protein source is entirely terrestrial plants, and the second in which the protein source is entirely marine fish. For simplicity, any effect due to terrestrial animal protein consumption (meat or

Table 3.1: *Dietary model of collagen $\delta^{13}C$ and $\delta^{15}N$ based on differences in direct carbon to collagen routing.*

Endpoints	δ^{13}C	δ^{15}N	
100% terrestrial plant	-21	4.5	$\delta^{13}C_{protein} = \delta^{13}C_{carbohydrate}$
100% marine	-12	12	

	100% C routing		50% C routing		Variable routing (90 to 50%)		
marine protein fraction	δ^{13}C	δ^{15}N	δ^{13}C	δ^{15}N	δ^{13}C	δ^{15}N	C protein fraction
0.0	-21.00	4.50	-21.00	4.50	-21.00	4.50	0.50
0.1	-20.10	5.25	-20.55	5.25	-20.48	5.25	0.58
0.2	-19.20	6.00	-20.10	6.00	-19.81	6.00	0.66
0.3	-18.30	6.75	-19.65	6.75	-19	6.75	0.74
0.4	-17.40	7.50	-19.20	7.50	-18.05	7.50	0.82
0.5	-16.50	8.25	-18.75	8.25	-16.95	8.25	0.90

cheese) has been eliminated. The first calculation assumes 100% direct routing of carbon (see Table 3.1, Figure 3.2). When the diet contains 50% marine protein, both the δ^{13}C value and the δ^{15}N value lie midway between the two dietary endpoints.

The second calculation assumes that 50% of carbon is consistently derived from non-protein sources, but that these non-protein sources are identical in δ^{13}C and δ^{15}N to the terrestrial protein sources. In this calculation the δ^{15}N remains unchanged. This 50% routing represents the minimum amount of carbon that must be derived from protein as determined experimentally (Jim et al., 2006). In the absence of information about protein quantity, quality, protein routing threshold, and individual variation, we can only be certain that the true variation must lie somewhere between these two lines (see Figure 3.2). The degree of direct protein routing likely varies depending on the quantity of protein in the diet. I have illustrated the potential isotopic effect of this by assuming a linear relationship between 50% direct routing at 0% marine diet, and 90% routing at 50% marine diet. This third line illustrates how slightly lower than expected δ^{13}C values could result. At 20% marine protein the δ^{13}C value is 0.6‰ lower than in the direct routing model.

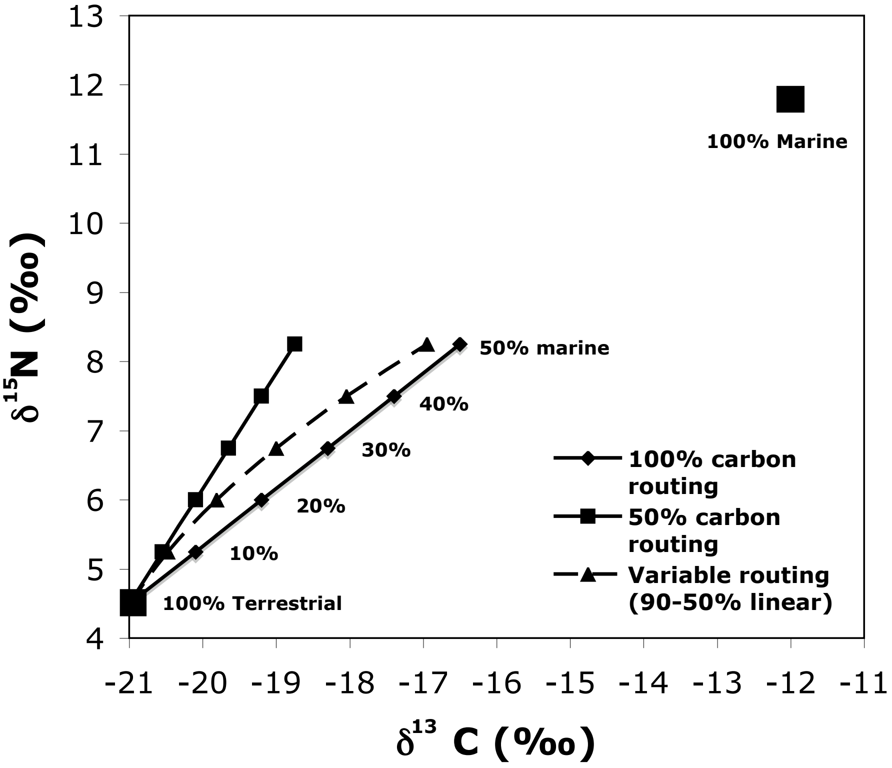

Figure 3.2: *Model of collagen $\delta^{13}C$ and $\delta^{15}N$ based on two extreme dietary end-points (marine and terrestrial plant) indicating variation due to assumptions about carbon routing*

Protein quality can also affect δ^{15}N in terms of the degree of trophic level fractionation. It was observed that low protein diets appeared to result in higher δ^{15}N values (Ambrose, 1991). Based on current experimental evidence it is uncertain whether increasing the concentration of nitrogen (protein) in the diet results in a large discrimination factor, which would mean the trophic level differences become increasingly large as one moves up the food chain, or whether increasing the concentration of nitrogen in the diet decreases the discrimination factor, resulting in carnivores having smaller offsets compared to herbivores than herbivores do compared to plants.

One group of controlled feeding experiments seems to show that high-protein diets result in relatively larger $\Delta^{15}N_{\text{diet-body}}$ fractionation (Pearson et al., 2003; Sponheimer et al., 2003a,b), while reviews of animal diets from ecological literature seem to show the reverse (Robbins et al., 2005; Vanderklift and Ponsard, 2003) or no effect (McCutchan et al., 2003). Sponheimer et al. (2003a) found that herbivores raised on a 19% protein diet had $\Delta^{15}N_{\text{diet-hair}}$ fractionation an average of 2.3‰ greater than those individuals on a 9% protein diet. The differences were $1.5 - 2.8$‰ depending on the species but were consistent across each of the four herbivore species studied. The authors suggested that the reason for this difference could be due to a change in the amount of nitrogen excreted in faeces relative to the amount excreted in urea for low- versus high- protein diets. Since herbivore faeces are enriched in ^{15}N by $0.5 - 3$‰ while urine is depleted by $0.5 - 5.0$‰, the low-protein diet could cause more nitrogen to be excreted in faeces, lowering the body's $\delta^{15}N$. On a high-protein diet a comparatively larger proportion of nitrogen is excreted through ^{15}N-depleted urine, raising the body's overall $\delta^{15}N$. Similarly, Pearson et al. (2003) found an increase in $\Delta^{15}N_{\text{diet-body}}$ fractionation for birds on high-protein diets compared to low-protein diets.

In their review of 21 avian and mammalian tissue-to-diet discrimination factors, Robbins et al. (2005) found a highly variable, but slightly negative, relationship between % dietary nitrogen and $\Delta^{15}N_{\text{diet-animal}}$. Vanderklift and Ponsard (2003) found that the trophic level $\delta^{15}N$ enrichment increased with the C/N ratio of the diet. However, their review only obtained C/N ratios for the diets of insects, molluscs, crustaceans and fish. There were not enough studies of the effect of diet-tissue $\delta^{15}N$ discrimination for larger animals, especially mammals, so it is unclear how well this trend can be applied. In their systematic review of the ecological literature, McCutchan et al. (2003) failed to find any significant differences between $\delta^{15}N$ values of consumers on high-protein diets compared to low-protein diets. However, of the 79 species that were included in this review, the majority were insects, and only six were mammals, making the application of their trophic level enrichments patterns to human dietary reconstruction difficult to extrapolate.

3.7 Summary

Stable isotope analysis in palaeodietary reconstruction is based on the principle that ‘you are what you eat’. The carbon and nitrogen isotopic ratios of food are incorporated into the body’s tissues, including tissues preserved after death, such as bone collagen. Carbon isotope ratios distinguish between different photosynthetic environments. Most foods available in Europe during the Roman and Medieval periods would have been C3 plants. Millet, and later sorghum, would have been available C4 plants with significantly higher δ^{13}C ratios. Carbon in marine environments has a different isotopic ratio from atmospheric carbon, and so marine δ^{13}C ratios resemble those of C4 plants. Nitrogen isotope ratios can distinguish between trophic levels, because the δ^{15}N of the consumer’s tissues is several per mille higher than that of the food they consume. Breastfeeding infants have higher δ^{15}N than their mothers. Legumes fix nitrogen directly from the atmosphere and therefore have lower δ^{15}N than other plants which obtain their nitrogen from a variety of sources in the soil. Nitrogen isotope ratios can be used to estimate the relative proportion of animal protein in the diet, although this is complicated by the uncertainty of knowing what the diet-to-consumer trophic level increase should be, as well as by other non-dietary factors that can influence δ^{15}N. Nitrogen isotope ratios in aquatic environments (freshwater and marine) can be significantly higher than terrestrial ratios, because of the greater complexity of aquatic food chains.

Based on these principles, it is possible to distinguish between a variety of food sources (see Figure 3.3). A lower consumption of animal meat, as hypothesized for the early Medieval period, would result in lower δ^{15}N. However, this simple pattern is complicated by several non-dietary factors that affect isotopic ratios. Altered metabolic states such as growth (including pregnancy) and starvation will affect the body’s δ^{15}N, but there has been no detectable effect in archaeological bone collagen. Long term heavy manuring has been shown to increase plant δ^{15}N by at least 3.5‰, and since the manure supply was limited

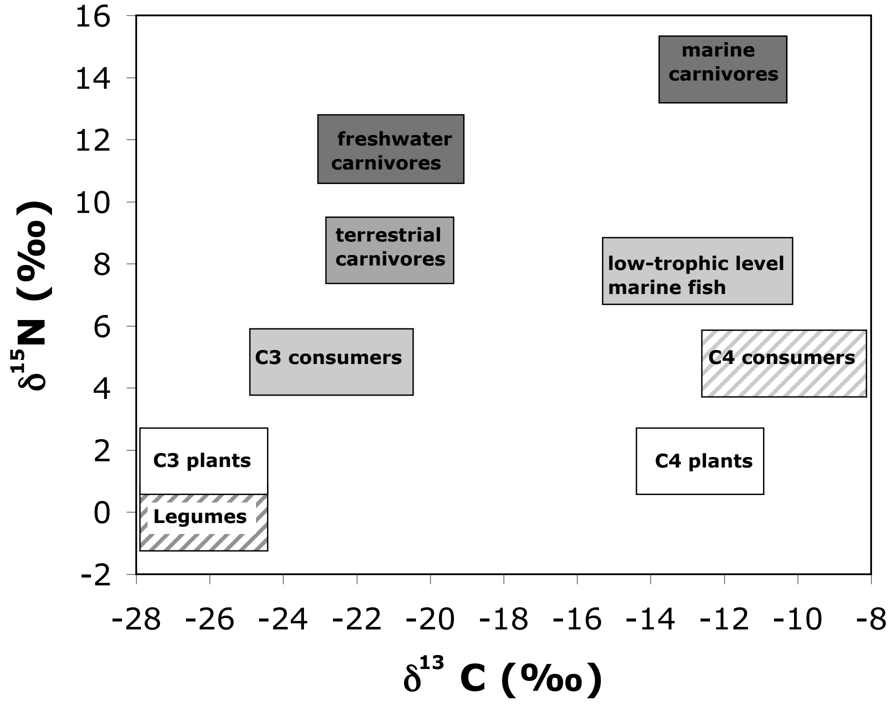

Figure 3.3: *Illustration of differences in* $\delta^{13}C$ *and* $\delta^{15}N$ *through the ecosystem. Note that actual isotopic ranges can differ significantly from the values suggested here due to a variety of complicating factors.*

in ancient agriculture, there is the potential for different foods to have widely different δ^{15}N ratios. Geography and climate also affect carbon and nitrogen isotope ratios. The nitrogen isotopic ratios that are taken up by plants are affected by local soil conditions, such as manuring, but also aridity and salinity. Carbon isotope ratios in plants vary according to broader climatic conditions (humidity, light, temperature) which affect the process of photosynthesis.

The protein collagen preserves well in bone and is present in large quantities, making it the ideal tissue to sample for palaeodietary analysis. The turnover time for this tissue is low, reflecting the dietary isotopic chemistry of the last several years of life, although this can vary according to the type of bone sampled. The nitrogen component of collagen must derive from the nitrogen of ingested amino acids. At least 50% of the carbon component derives from protein, probably as much as 90%. Low protein diets encourage the synthesis of non-essential amino acids, incorporating carbon from non-protein sources into collagen. In addition, low-protein diets may also affect the trophic level discrimination factor for δ^{15}N, although the experimental evidence is ambiguous. All these sources of variation will affect the interpretation of stable isotope ratios for dietary reconstruction in Roman and Medieval Europe.

4

Material and Methods: Stable isotope analysis in central Italy and meta-analysis of European data

In this chapter I describe the eight archaeological sites from Roman and Medieval central Italy that were sampled for isotopic analysis. I discuss the analytical methods, including measures of data quality. The results of these analyses are presented in Chapter 5. The second half of this chapter describes the methods employed for the meta-analysis of previously published stable isotope data for sites from Europe and the Mediterranean, dated AD 1-1500. This analysis will be presented in Chapter 6.

4.1 A brief review of previous Italian isotopic studies

The sites selected for this study were designed to complement the existing isotopic data from Roman and Medieval Italy. The aim was to use the previously published data, in conjunction with the newly sampled individuals from different periods, environmental zones and types of settlement, to provide a more complete picture of dietary practices through time.

Most of the previous isotopic studies of Italian material date to the Roman period and come from coastal sites, usually large urban centres (see Table 4.1 and Figure 4.1). Sites were classified as coastal that were $<$ 10km from the coast. Urban sites were those collections of human remains that were associated with a town or city. The rural sites are those collections of humans that were not associated with a town or city, and were generally found as the result of salvage excavations. These studies include Etruscan settlement (8th to 3rd century BC) at Pontecagnano located on the coast of Italy south of Naples (Scarabino et al., 2006). The Greek colony at Metaponto (7th to 2nd century BC) has also been analysed (Henneberg et al., 1999; Pate, pers. comm.). The first study of Roman individuals from Italy was the extensive work at the Isola Sacra necropolis of Rome's harbour, Portus, by Prowse et al. (2008, 2004, 2005), and followed up by Crowe et al. (2010). A small population known as ANAS, located 12 km away from the coast and near Rome has also been studied (Prowse et al., 2004). Craig et al. (2009) analysed a second harbour town, Velia, located south of Naples. Some individuals from Pompeii have also been analysed, but remain unpublished (Pate, pers. comm.). Late Roman Christians were analysed from the catacombs of St Callixtus outside of Rome (Rutgers et al., 2009). These results are discussed in more detail in Chapters 5, 6, and 7.

4.1.1 Previously published Roman Italian sites

The site of Isola Sacra was a cemetery for the inhabitants of Portus, the port city that served Rome at the mouth of the Tiber (Prowse et al., 2008, 2004, 2005). On average, Isola Sacra humans had high δ^{15}N (5.5‰ higher than herbivores from the same site) without a corresponding elevation in δ^{13}C that would be indicative of marine fish consumption. This was contrary to the expectation from both historical and archaeological sources that the Romans would have eaten large amounts of fish (see Figure 4.2). The human δ^{15}N was

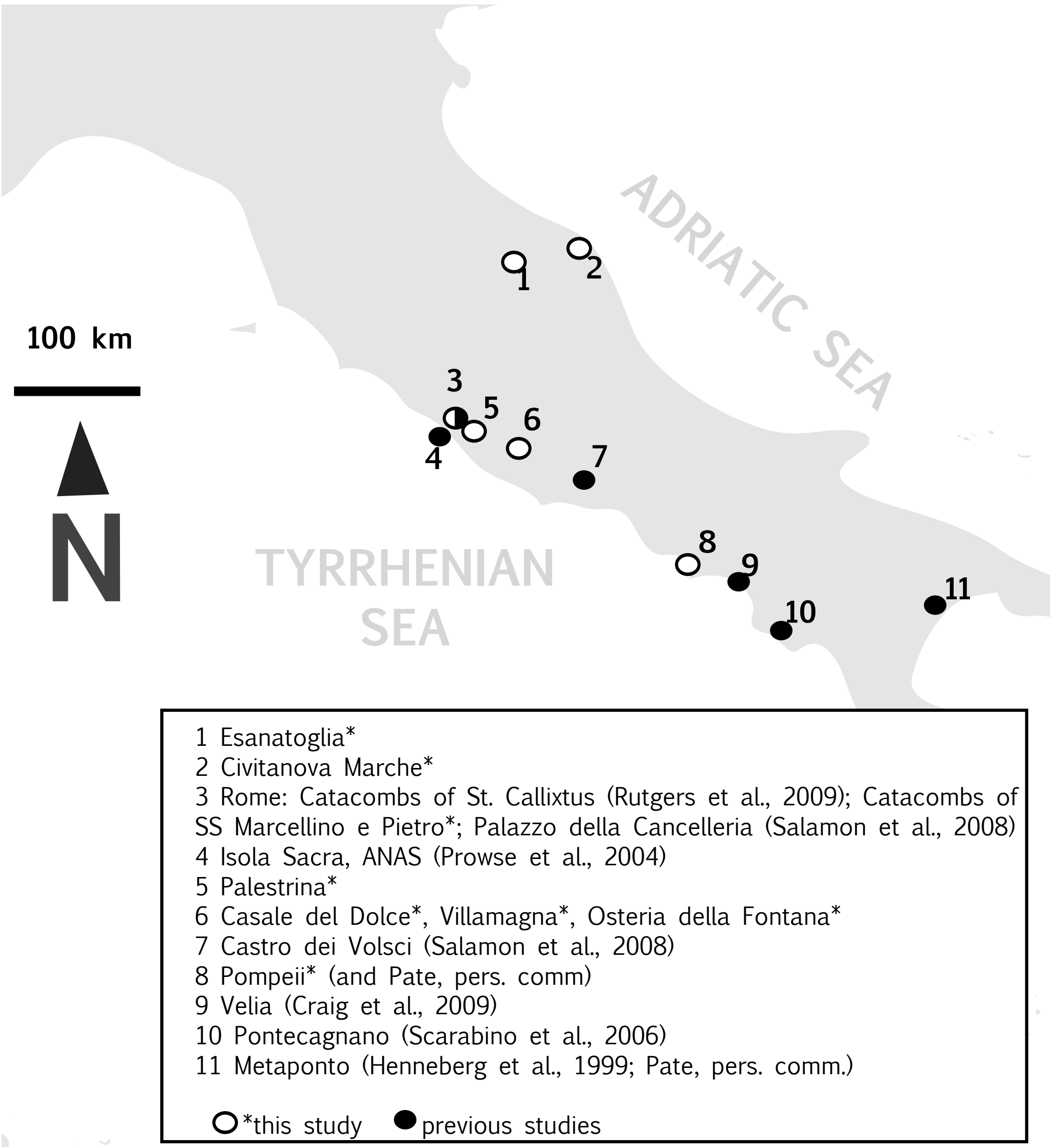

Figure 4.1: *Map of Italy showing sites sampled for this study and previously published sites.*

higher than what would be expected for a single trophic level shift. Since the pig δ^{15}N values were within the range of the herbivores there was no evidence to suggest the consumption of omnivorous pig meat as an explanation for the high human δ^{15}N. Prowse et al. (2004) also presented human results from a site ('ANAS') several kilometers inland from Isola Sacra. Here δ^{15}N and δ^{13}C were both lower than at Isola Sacra (see Figure 4.2), suggesting a strong influence

Table 4.1: *Summary of sites from previously published studies. N = number of humans. 1 Scarabino et al., 2006; 2 Henneberg et al., 1999; 3 Prowse et al., 2004; 4 Crowe et al., 2010; 5 Craig et al., 2009; 6 Rutgers et al., 2009; 7 Salamon et al., 2008; 8 Fornaciari, 2008; 9 Pate, pers. comm. All dates AD unless indicated otherwise.*

Ref	Site	Date	N	Location	Type
1, 9	Pontecagnano (Sant' Angelo and Library)	8th-3rd C BC	18	Coastal	Urban
2	Pantanello (Metaponto)	7th-2nd C BC	23	Coastal	Urban
2	Crucinia (Metaponto)	7th-2nd C BC	25	Coastal	Urban
3, 4	Isola Sacra	1st-3rd C	189	Coastal	Urban
9	Pompeii	1st C	31	Coastal	Urban
3	ANAS	1st-3rd C	14	Inland[a]	Rural
5	Velia	1st-3rd C	117	Coastal	Urban
6	St Callixtus, Rome	3rd-5th C	22	Inland[b]	Urban
7	Castro dei Volsci	5th C	13	Inland	Rural
7	Rome—Palazzo della Cancelleria	15th C	36	Inland[b]	Urban
8	Florence, Medici Grand Dukes	16th-17th C	20	Coastal	Urban
8	Naples—Aragonese Princes	15th-17th C	25	Coastal	Urban

[a] ANAS is 12km from the modern coast.

[b] Rome is 25km from the modern coast.

in the diet of the residents of Isola Sacra due to their proximity to the sea.

The analysis of Roman human and fauna from Velia, Italy, also revealed lower than expected amounts of marine fish consumption. Velia was a port city, although was less significant than the city of Portus in which the Isola Sacra population lived. In the stable isotope analysis performed by Craig et al. (2009) two distinct dietary groups emerged. Most of the population had low δ^{15}N and consumed relatively little meat and marine fish, and probably large amounts of cereal. This was inconsistent with the accounts of the 1st century AD writer Strabo, who suggested that the agricultural territory of Velia was poor enough to have forced its residents into making a living from the sea. A smaller portion of the population, mostly male, had high δ^{15}N relative to the animals from the site (see Figure 4.2). The high δ^{15}N was interpreted as the result of a marine diet, although there is little corresponding increase in δ^{13}C.

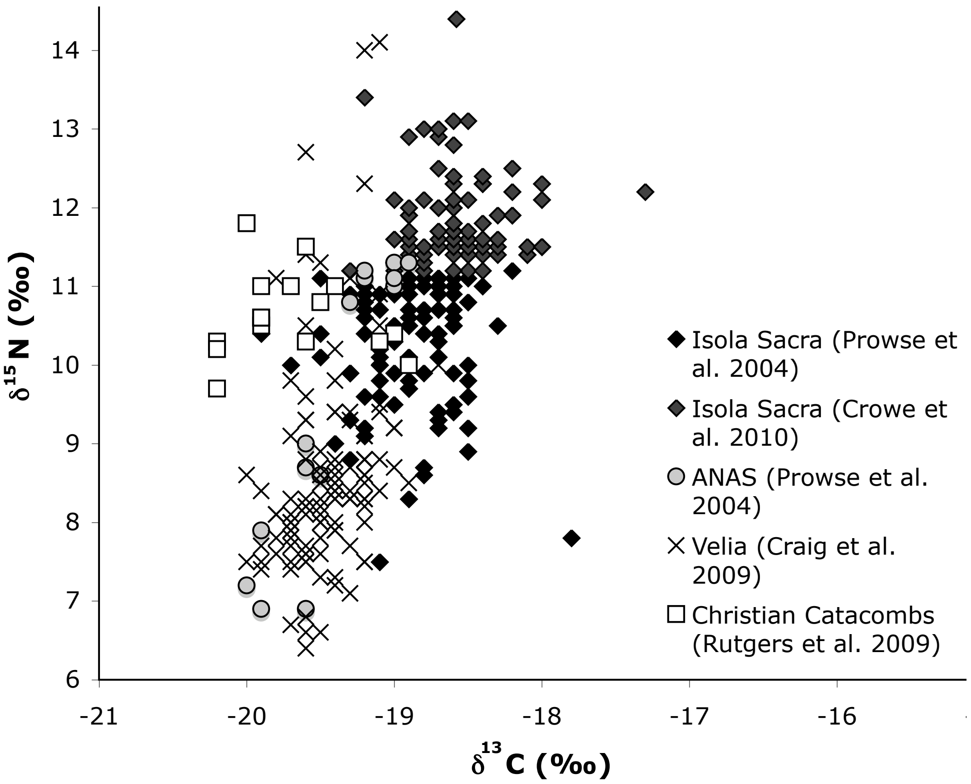

Figure 4.2: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for humans from previously published Roman Italian sites*

The highest δ^{13}C value from the site is $-18.8‰$, compared to their reported mean value of marine fish of $-13.7‰$. On average, δ^{13}C and δ^{15}N is lower at Velia than at Isola Sacra.

Further study of the material from Isola Sacra and Velia, including additional sampling of individuals from Isola Sacra for stable isotope analysis, found a correlation between high δ^{15}N and an abnormal bone growth on the ear (Crowe et al., 2010). This condition, called external auditory exostoses, is associated with water-related occupations, specifically prolonged exposure to cold water related to fishing or diving. This condition was confined almost exclusively to males and was more prevalent among males from Velia (35.3%) than Isola Sacra (21.1%).

A small sample of Christians buried in the catacombs of St Callixtus outside Rome provided calibrated radiocarbon dates c. AD 130, for the supposed founding date of the tomb around AD 200 (Rutgers et al., 2009). This group was also analysed for stable isotopes, and the relatively high δ^{15}N values with lower δ^{13}C than either Isola Sacra or Velia (see Figure 4.2), along with the radiocarbon offset suggested that freshwater fish had been consumed. On the basis that fish, and especially freshwater fish, would have been an important protein source for the urban poor, the authors suggested that these Christians ate fish more out of poverty than out of a desire to express religious devotion. The isotopic ratios of the individuals from the catacombs of St Callixtus are distinguished from Isola Sacra and Velia by the lower δ^{13}C.

At Isola Sacra and Velia the same pattern of high δ^{15}N with relatively low δ^{13}C was noted for humans. The low δ^{13}C value suggests a diet containing less fish than expected from historical information for the Roman period. Sources of high δ^{15}N but low δ^{13}C foods could have been omnivore meat or freshwater fish. Prowse et al. (2004) suggested that isotopic routing factors, rather than dietary factors, could explain the pattern. If the Roman diet was low in protein, carbon from the bulk diet might have been used to synthesize many of the non-essential amino acids in collagen, and would result in bulk δ^{13}C ratios with a more terrestrial value (terrestrial plants being the only significant source of carbohydrate), whereas the δ^{15}N value would reflect only the elevation due to the consumption of marine food. This explanation was also favoured by Craig et al. (2009) for Velia and Keenleyside et al. (2009) for Roman Leptiminus (Tunisia). The question of Roman fish consumption and the isotopic routing hypothesis are explored more fully in Chapter 7.

4.1.2 Previously published Medieval Italian sites

The post-Roman period in Italy has received less attention from palaeodietary analysis. Salamon et al. (2008) compared a 6th century inland rural population from southern Lazio (Castro dei Volsci) to a 14th century population from Rome (Palazzo della Cancelleria). The 13 individuals analysed from the 6th century population of Castro dei Volsci have a low average δ^{15}N of $7.4 \pm 0.5‰$ (Salamon et al., 2008). The high average δ^{15}N ($11.0 \pm 1.8‰$) among the 36 15th century individuals from the Palazzo della Cancelleria in the Campus Martius in Rome was interpreted as evidence for a large amount of fish consumption. The authors suggested that the differences in diet between the early Medieval inland site of Castro dei Volsci, and the late Medieval urban group from the Palazzo della Cancelleria were related to the opening of the North Atlantic cod trade c. AD 1000, in accordance with the zooarchaeological evidence from Medieval Britain presented by Barrett et al. (2004a). However, Salamon et al. did not take into account the potential differences between urban and rural sites, making generalizations from such a comparison difficult. In addition, the lack of marine enrichment in δ^{13}C at Palazzo della Cancelleria (the average is -19.0 ± 0.4‰) makes it unlikely that high levels of marine fish consumption were the primary cause of the dietary difference.

Fornaciari (2008) analysed δ^{13}C and δ^{15}N in Italian Renaissance princes from Florence and Naples. The individual data were not published, but estimating from graphs of the results shows that the Medici princes in Florence had slightly higher δ^{15}N on average (between 11.2 and 14‰) and the Aragonese princes based in Naples had more enriched δ^{13}C (between -19 and -16.8‰). In general the high δ^{13}C and high δ^{15}N was interpreted as the result a large amount of marine fish in the diet, indicative of the high status of these burials. The lack of comparative faunal material, the elite status of these individuals, their slightly later date (16th-17th century) limit the extent of useful comparisons that can be made.

4.2 Archaeological Context

The aim of this study was to examine long-term dietary change in Italy c. AD 1-1500 by undertaking new isotopic analyses which complement the existing data. Coastal locations in Italy had already been well-studied, but the results proved ambiguous to interpret. The likely presence of consistent low levels of marine food, regardless of wider social, political or economic circumstances, made other dietary patterns difficult to observe. For this study, it was essential to focus on samples from a single region within Italy, located away from the sea, where dietary patterns could be related to broader trends in Roman and Medieval Europe.

The focal point of this study was the sequence of Early to Late Medieval burials recently uncovered by the excavations at Villamagna, a Roman Imperial villa-turned-monastery in the modern region of Lazio. Additional nearby sites were chosen to obtain a cross-section of individuals from rural Lazio, ranging from the 1st to the 15th centuries AD. This area was under the control of Rome/Byzantium during Late Antiquity, and continued to have strong ties with Rome throughout the Middle Ages. An early Roman/late Iron Age context from Palestrina (4th-3rd century BC) was also included for comparison. Additional samples were chosen from a site (Esanatoglia) in the Lombard-controlled region of Marche, which borders Lazio to the north-east. All sites were chosen to obtain information about a range of urban, rural, coastal and inland environments, complementing the data from previous studies. See Table 4.2 for a summary of the sites sampled.

4.2.1 Roman sites

Table 4.2: *Summary of sites selected for isotopic analysis. N is total number of humans (fauna) included in the analysis*

Ref	Site	Date	N		Location	Type
This study	Palestrina	4th-3rd C BC	9		Inland	Urban
	Osteria della Fontana	1st C AD	14		Inland	Rural
	Pompeii	1st C AD	22		Coastal	Urban
	Casale del Dolce	1st-4th C AD	66		Inland	Rural
	Civitanova Marche	3rd-4th C AD	29		Coastal	Urban
	Marcellino e Pietro, Rome	3rd-5th C AD	12		Coastal	Urban
	Esanatoglia	6th-8th C AD	11		Inland	Rural
	Villamagna	5th-15th C AD	206	(29)	Inland	Rural
TOTAL			369	(29)		

Lazio, on of the Tyrrhenian side of Italy, is characterized by a coastal plain and is bordered by the Apennines along the north-east. Much of the region is flat, fertile plains. South of Rome, a small chain of mountains rises between the Apennines and the sea, the Monti Lepini, which create a long, broad valley following the course of the Sacco and Liri rivers (see Figure 4.3). Like most regions of Italy, this area is characterized by complex agricultural patterns, with coastal plains, fertile volcanic hills, areas of poor soil and significant climatic differences between uplands and lowlands (Arthur, 2004).

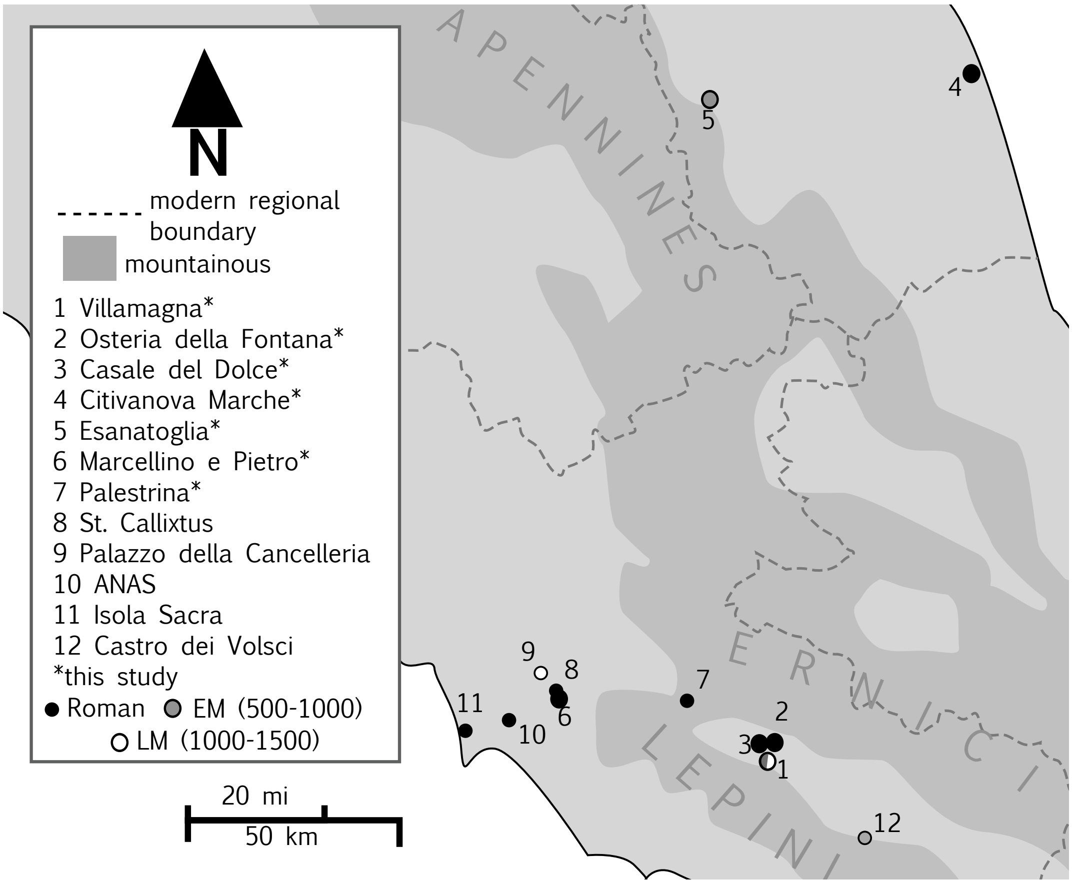

Figure 4.3: *Map of central Italy showing sites sampled for this study and previously published sites.*

The modern region of Lazio was originally called Latium by the Romans after the Latin tribes that populated the area. Latium was one of the first territories conquered by the expanding Roman republican city-state in the 4th and 3rd centuries BC. It became part of Region I in the province of Italia under the system devised by the first Roman emperor, Augustus. The interior valley between the Lepini and Ernici mountains was of strategic importance. After the construction of the Via Latina, begun in 334 BC, it became a crucial communication route between Rome and its southern Italian territories. This road was the main artery in a system of minor roads throughout the area (Nicosia, 1995, 8).

Palestrina was an important inland town in the pre-Roman period located in the northern part of the Sacco river valley about 30km east of Rome (see Figure 4.3). It was one of the last Latin towns to fall under Roman rule, and there are many burials with rich grave goods imported from Greece and Etruria, including bronze mirrors, strigilium, and black- and red-figure pottery (Rubini, pers. comm.).

The site called Villamagna was recorded in classical times by a letter of Marcus Aurelius. On the basis of this reference and the name (*villa magna* meaning 'great villa') it was likely an important Imperial property. The site remained unexcavated until the work of the team led by Elizabeth Fentress and Caroline Goodson from 2004 to 2010. The results of the excavation have been published as preliminary reports (Booms et al., 2008; Fentress et al., 2007, 2006, 2009, 2010).

Villamagna is located in the foothills of the Monti Lepini, overlooking the Liri Valley, through which the Via Latina ran in classical times. Excavations have revealed a large area of Roman occupation; the presence of a bath complex, wine-processing area, and opulent marble tile make it likely the villa was owned by the Imperial elite. The excavations also uncovered non-elite residential structures which may have been domestic structures for slaves. No necropolis associated with the population of the villa has been discovered (Fentress et al., 2010). Four faunal bones originating from Roman midden contexts at the villa were sampled for isotopic analysis. The medieval occupation at Villamagna is discussed below.

Due to the absence of burials associated with Villamagna, nearby sites were chosen for isotopic analysis. Casale del Dolce is a Roman cemetery located at the base of the Sacco river valley, 4km from Villamagna (see Figure 4.3). These Roman burials are of simple cappucina type, dating from the 1st to the 4th century AD. The lack of high quality grave goods accompanying these burials suggests that it was not an elite population, but likely war veterans (Zarattini and Petrassi, 1997). Fifty-nine adults were analysed from Casale del Dolce and an additional seven infants.

A further 14 individuals were sampled from a series of Roman burials uncovered in the village of Osteria della Fontana just outside the modern city of Anagni, located 6km from Villamagna. These burials were discovered as part of a larger excavation of archaic and palaeolithic remains at the site (Gatti, 1993). These excavations indicated that the territory around Anagni was characterized by large *latifundia* type villas and also small family farms. The individuals analysed here date from the Roman period (1st century AD). Similar to nearby Casale del Dolce, these individuals were buried in simple cappucina tombs with few grave goods. The population represented by the burials at Osteria della Fontana would have had close links with the large Roman villa that existed at the site of Villamagna at the time (Gatti, 1993).

To provide an urban comparison for developments in rural Lazio at this time, 12 individuals were analysed from the catacombs of SS Marcellino e Pietro in Rome. These individuals provide a key comparison for previously published sites. They provide a late Antique perspective on Christian diets, supplementing the dietary information about early Christian diets provided by Rutgers et al. (2009). This site also provides a comparison for the early Christian catacombs of St Callixtus analysed by (Rutgers et al., 2009).

An additional 22 adults were sampled from Pompeii, located just off the coast, 150km to the south of Villamagna. These individuals from the 79 AD destruction layer were included because they were expected to have consumed large amounts of seafood. The analysis of this site supplements the information provided by the two previously published coastal Roman stable isotope studies, and provides a further comparison for the two inland Roman sites in this study.

All previously-analysed Roman sites come from the Tyrrhenian side of Italy. To provide a perspective on diet in other areas of Italy, Civitanova Marche, located in the region of Marche (ancient Picenum) on the Adriatic coast was analysed in order to provide dietary information about a previously unstudied region of Roman Italy. The 21 adults from Civitanova Marche date from the 3rd to 4th century AD. The site was an important port during the Roman period for trade along the Adriatic and into the Balkans. Like the other Roman sites analysed for this study, the graves were cappucina tombs with simple grave goods.

4.2.2 Early Medieval Samples

The social, political and economic changes that occurred at the end of the Roman empire are observed on a more local scale in central Italy. The rural population was isolated from urban centres, and concentrated in larger settlements, while many sites were abandoned, ceasing to be mentioned in literary sources from the late 3rd/4th century onwards (Nicosia, 1995, 37-44). At Villamagna, an apsidal building was constructed in the last half of the 3rd century AD, which may have been converted to a church at some point in the 4th or 5th century (Fentress et al., 2010). This is consistent with the archaeological evidence for the spread of Christianity in the rest of Lazio. Theodosius made Christianity the official religion of the Empire in 380. Inscriptions, architecture and textual references suggest that the new religion began to take hold in coastal areas from the 3rd century AD, spreading to the interior in the 4th and 5th centuries (Nicosia, 1995, 21-33). During the political turmoil of Late Antiquity, the Liri and Sacco valleys offered defensible positions in the foothills of the mountains and seem to have been settled by the rural population (Nicosia, 1995, 42).

Occupation at the Imperial villa at Villamagna began to decline as early as the 3rd century AD, and there are no finds from the site datable to AD 470-550, suggesting a period of abandonment (Fentress et al., 2010). This abandonment coincides with the Byzantine-Gothic wars (see Chapter 1). During the Byzantine-Gothic wars the area of southern Lazio was strategic for the movement of troops from the south up to Rome, and also became a focus for military conflicts. In the later part of the war, the balance of power in southern Lazio repeatedly swapped between Byzantine and Gothic forces, with the inhabitants of the region being forced to switch allegiances in order to survive (Nicosia, 1995, 54-55). After the Byzantine-Gothic wars, control of the Italian territory was divided between separate ruling powers, a division which persisted up until the modern unification. Throughout this period, the area of southern Lazio remained near the border between separate jurisdictions (Wightman, 1994). Lazio generally experienced an economic revival between the Byzantine-Gothic wars and the arrival of the Lombards in the late 6th century. This was partly because control of the few remaining agricultural resources was consolidated in the hands of ecclesiastical authorities (Nicosia, 1995, 61). At Villamagna, the rebuilding of the apsidal building as a church, and the conversion of the old portico into a wine storage facility suggest that the site was being used as an important economic centre and as a source of tax revenue for Imperial (Roman/Byzantine) authorities (Fentress et al., 2010). There is no available burial material from this time. Dietary information from Lazio in the 6th century can be obtained from the 13 individuals previously analysed from Castro dei Volsci, located 30km to the south-east in the same river valley system (Salamon et al., 2008).

In the 6th century, the arrival of the Lombards in Italy brought renewed disruptions. A contingent of Lombards under Zotto took control of southern Italy up to the southern end of the Liri valley, but were not able to progress further north. Many cities in Lazio were abandoned in the 6th century, and many of the remaining cities were conquered by the Lombards, including Aquino in 577, and briefly Monte Cassino as well (Nicosia, 1995, 70-71). The area to the north of the Lombard territory, including Villamagna, remained in the hands of the pope in Rome, nominally controlled by Byzantium. The Byzantine authorities continued to resist the Lombard forces to the south, creating a relatively permanent division at the southern end of the Liri valley, across what had once been an important Roman communication route, the Via Latina. The period from the 6th century to the end of the 8th century was relatively stable for the local population and Lombards and Romans would have lived side-by-side (Nicosia, 1995; see Figure 4.4).

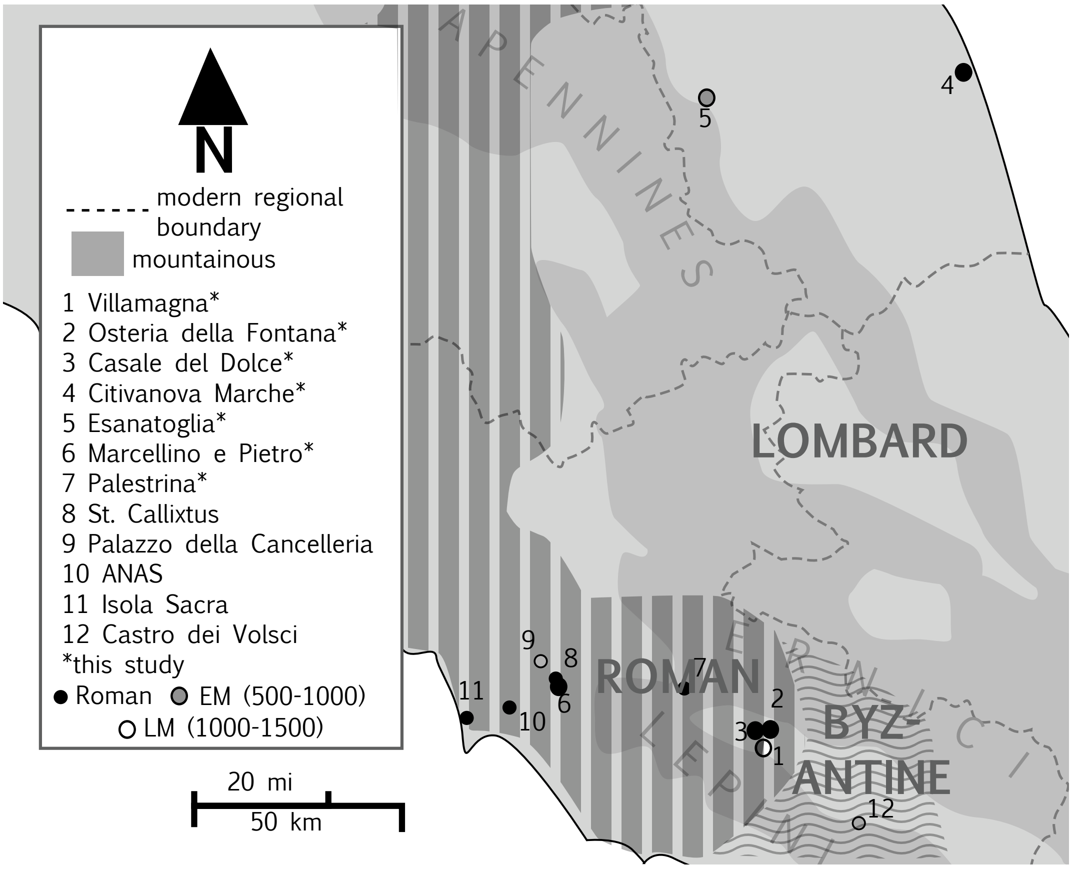

Figure 4.4: *Map of central Italy showing sites sampled for this study and previously published studies. Political boundaries show territorial divisions in AD 774 prior to the Frankish invasion (based on Berit Lee in* Historical Atlas of the World*, Edinburgh, 1970)*

At Villamagna, post-holes and sunken buildings suggest habitation resumed, although using more ephemeral construction than in Roman times. These sunken floor buildings are possibly a sign of Lombard occupation, but have also been associated with non-Lombard contexts across Europe (Fentress et al., 2010). A possible palisade and ditch dating from this phase suggest that defensive structures may have been important. However, the absence of late 7th- or 8th-century pottery suggests that this site was once more abandoned, but re-occupied in the 9th century (Fentress et al., 2010). Six individuals were analysed from Villamagna dating from c. 700-1000.

In order to obtain information about the potential Lombard influences on Medieval diet, one site was analysed from Lombard-occupied territory, in the modern region of Marche. Like Lazio, the area of modern Marche continued to be politically and economically important in the 4th century. However in late Antiquity there are historical references to large numbers of peasants dying from famines, and a reduction in tax-generated revenue from the church (Christie, 2006, 36-7). Esanatoglia is the modern name of a village in the hilly terrain of the Apennines, located 450m above sea level. The settlement was known as Aesa in the Roman period, and was part of the Lombard-controlled Duchy of Spoleto. Eight adults, two juveniles and one infant were sampled from the 6th to 8th century Lombard-period excavations.

4.2.3 Late Medieval Samples from Villamagna

In the early 9th century the economic and administrative consolidation noted elsewhere in Europe can also be traced in the archaeology of central Italy (see Figure 4.5). This was the processes of *incastellamento*, the deliberate coalescence of farmsteads into fortified villages. By the beginning of the 9th century this is observed at Villamagna. Hundreds of post-holes suggest a medieval village was present on the site of the old Roman villa, surrounded by a wall (Fentress et al., 2010). Around the site of the church, the monastery of S Pietro di Villamagna was constructed. The foundation documents for the monastery are preserved at Anagni and indicate a date of AD 976 (Flascassovitti, 1994, n.1, 2). The monastery continued to be expanded and re-organized from the 11th to 13th centuries. A cloister and cistern were added to the north of the church, and a bell tower was constructed c.1100 (Booms et al., 2008; Fentress et al., 2009). Twenty individuals were analysed from this phase.

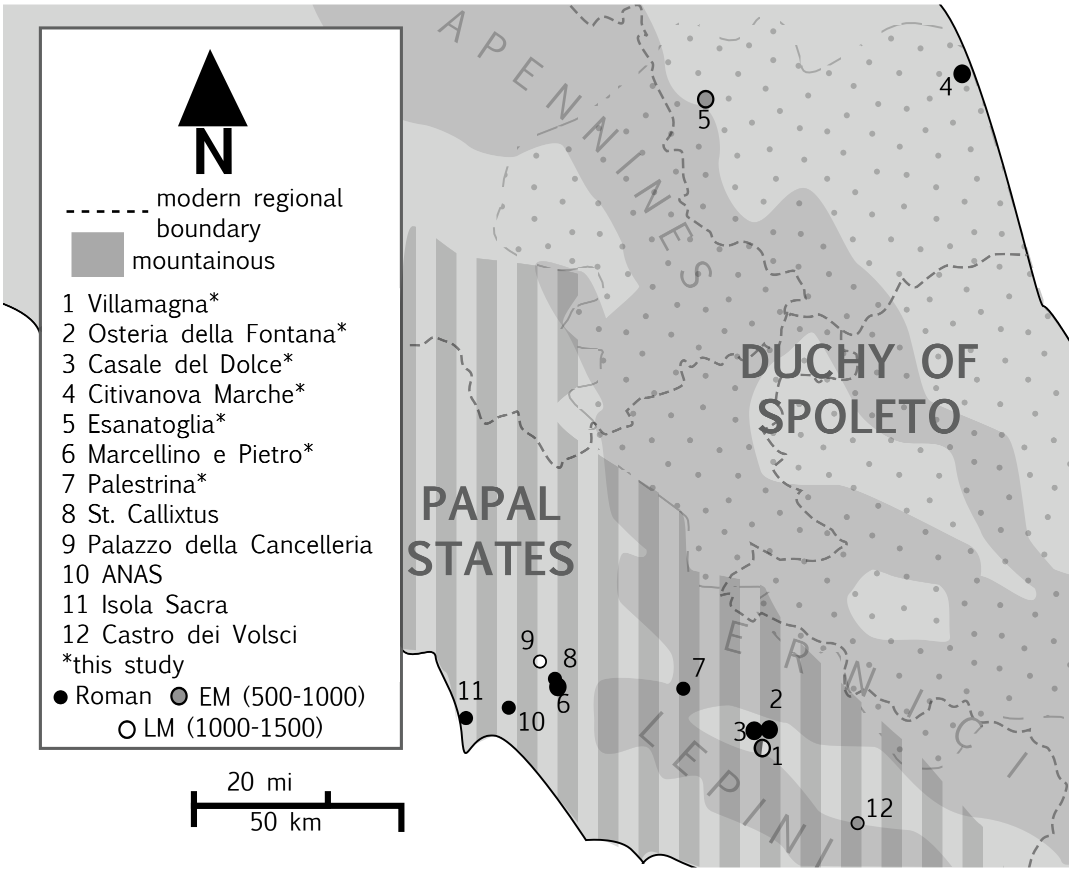

Figure 4.5: *Central Italian sites showing political boundaries c. 1050 (based on* The Historical Atlas*, William R. Shepherd, 1923)*

The monastery was suppressed in 1299, and the land likely came under the control of an elite family connected with the nearby city of Anagni. A large defensive wall was built in the 14th century, perhaps as a result of ongoing conflicts with nearby villages, noted in historical records. By 1458 the settlement at Villamagna was abandoned (Booms et al., 2008; Fentress et al., 2007, 2006). An additional 22 animal bones (sheep/goat, pig, cattle and horse) were analysed from 12th-15th century contexts from Villamagna. A total of 173 individuals were sampled from the late- to post-monastic phases (c. 1250-1500), male and female adults, juveniles and infants. A large number of samples were taken in order to examine dietary differences across different parts of the site. Some individuals were interred as multiple burials in what could have been family tombs. A subset of burials may have been the elite patrons of the site and were interred within the church itself. Some individuals were buried with jewellery (mostly rings) while the majority of burials had no associated grave goods. The large number of burials sampled permits intra-site dietary differences to be examined. The results from the population of Villamagna will also be compared to the previously analysed late Medieval Italians from the Palazzo della Cancelleria in Rome (Salamon et al., 2008) and the Renaissance aristocracy from Florence and Naples (Fornaciari, 2008). It is expected that the rural, inland location of Villamagna will provide a more representative picture of diet in late Medieval Italy. In addition, the wider context of the new Italian analyses presented here was examined through a meta-analysis of all previously published data from Roman and Medieval Europe. The methods that were employed in the design of this meta-analysis are discussed in 4.5 below.

Table 4.3 provides the approximate absolute dates for the chronological periods at Villamagna. Figure 4.7a shows the number of individuals analysed from each phase. By far, the majority of individuals date to the period after AD 1000, the bulk assigned to the Late Medieval phase. Adult ages were given as ranges (i.e. ‘18 to 20’), from which midpoint estimates were taken. Adults were those individuals whose midpoint age estimate was greater than or equal

Table 4.3: *Chronological phases at Villamagna and approximate absolute dates. Note that these phases include occupational gaps and some overlap.*

Date (AD)	Phase Name
400-600	Late Antique
700-950	Early Medieval
950-1250	Central Medieval
1250-1500	Late Medieval

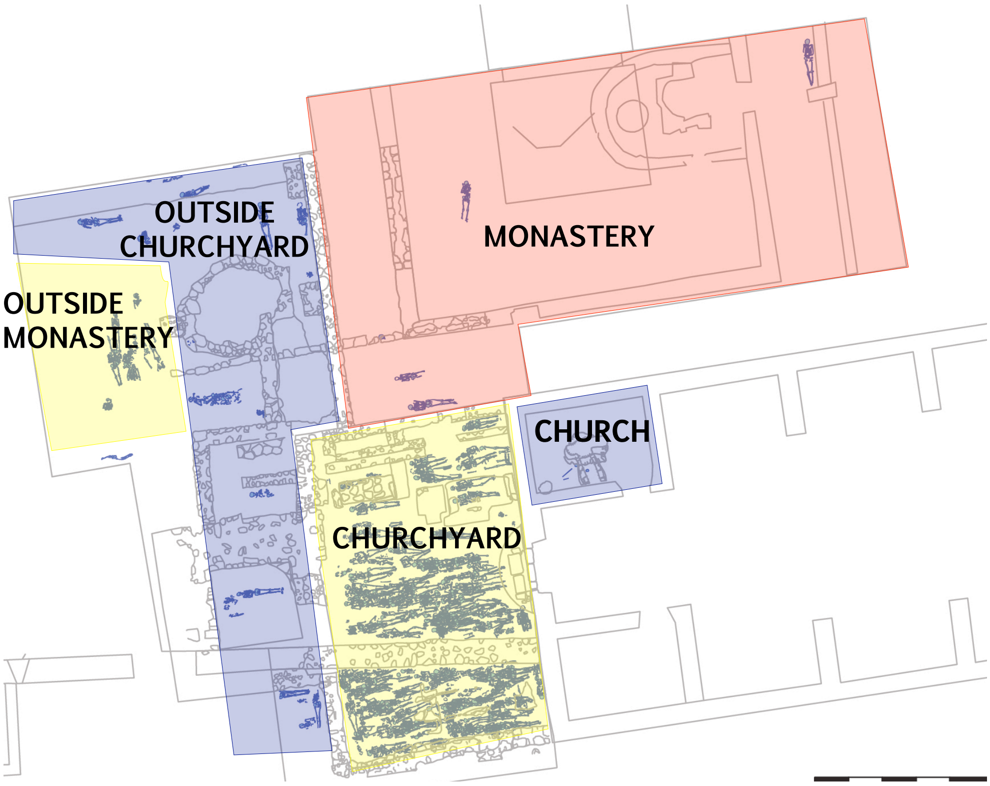

Figure 4.6: *Map of Villamagna showing different areas of the cemetery referred to in the text. Map from Caroline Goodson.*

to 16. Infants were individuals whose midpoint age estimate was less than or equal to 2. Juveniles were those subadults with midpoint age estimate greater than 2 and less than 16. Approximately equal proportions of Adults, Juveniles and Infants were sampled from all periods. The exception are the four Late Antique infants buried in a separate part of the site, which were omitted from the discussion of overall site trends. The rest of the medieval burials come from main part of the medieval site, the area around the church and monastery. This area can be divided into five separate locations, which also partly relate to the stratigraphy of the site (see Figure 4.6). From Figure 4.7b it is clear that individuals outside the monastery date from from the Central Medieval phase. Grave objects such as jewellery or clothing accessories were associated with a small number of the burials. The majority of individuals were buried on a W-E axis, but it is notable that the 'Outside Monastery' group is predominantly

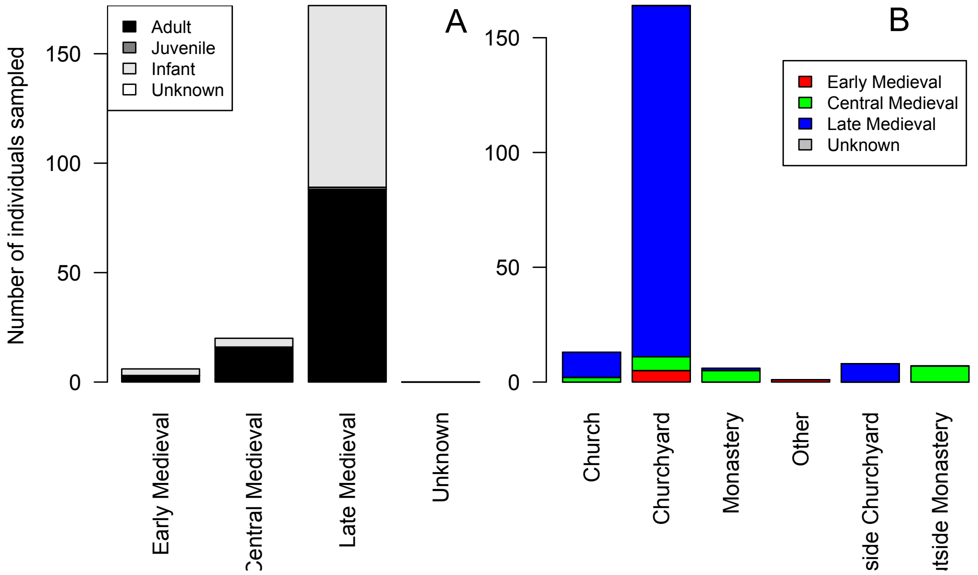

Figure 4.7: *Distribution of Medieval samples from Villamagna recovered from different phases and locations at the site A) Bar plot showing the number of individuals from different age categories sampled from different chronological periods, B) Bar plot showing the distribution of different phases across different location categories within the Villamagna monastery area.*

N-S.

4.3 Sampling, Collagen Extraction and Data Analysis

Bone samples for Palestrina, Casale del Dolce, Osteria della Fontana, Civitanova Marche, Marcellino e Pietro, and Esanatoglia were provided by Mauro Rubini and the Soprintendenza per i Beni Archeologici del Lazio. For these sites, anthropological information was not available, because the skeletal material had been obtained as a result of salvage excavations. For these sites, I provided an approximate age estimation, dividing the individuals into three categories: 'adult', 'juvenile' and 'infant' based on standard osteological characteristics (White and Folkens, 2005). Adults are those individuals who are skeletally mature, of adult stature and with long-bone epiphyseal fusion complete. Infants are those individuals less than about two years of age, potentially young enough to still be breastfeeding (and therefore to exhibit elevated δ^{15}N). This determination was based size of long bones, and epiphyseal fusion, since full skeletons were not usually available to make an assessment based on dentition. Juveniles are those subadults who are old enough not to retain a breastfeeding signal, but who had not reached their full adult stature. For these individuals, long-bone length and epiphyseal fusion indicated approximate age. The Villamagna samples were obtained from recent excavations coordinated by Caroline Goodson and Elizabeth Fentress. For the Villamagna individuals, anthropological information was provided by Francesca Candilio, Samantha Cox and Rowan Brixley.

Ribs were sampled where possible, but other skeletal elements were used as available, details of which are provided in Appendix A. For faunal samples, diagnostic skeletal elements were selected. Identification of animal species was provided by Julie Hamilton at the RLAHA, Oxford. Collagen was extracted using a modification of the Longin method (Longin, 1971) described by Honch et al. (2006). Ribs were cleaned using aluminium oxide shotblast powder. Then bone was demineralized in 0.5M HCl at 7°C for several days and acid was changed as necessary. The demineralized bone was rinsed three times in purified (Milli-Q) water and then gelatinized in pH3 water for 48 hours at 65°C. The supernatant liquid was decanted using an Eezi filter, and was freeze dried for several days until only collagen remained.

The majority of samples were analysed in triplicate to ensure reproducibility. Some were analysed in duplicate and a few as singles only. These are indicated in the data tables in Appendix A. Samples were analysed on a Carlo Erba 1108 carbon and nitrogen elemental analyser, coupled to a Europa Geo 20/20 mass spectrometer (PDZ Europa, Sandbach, UK) in continuous flow mode. An alanine standard was used to calibrate all runs. The nitrogen standard value used to calibrate the mass spectrometers changed in 2009, and so a 0.2‰ correction factor needed to be applied to some of the δ^{15}N measurements,

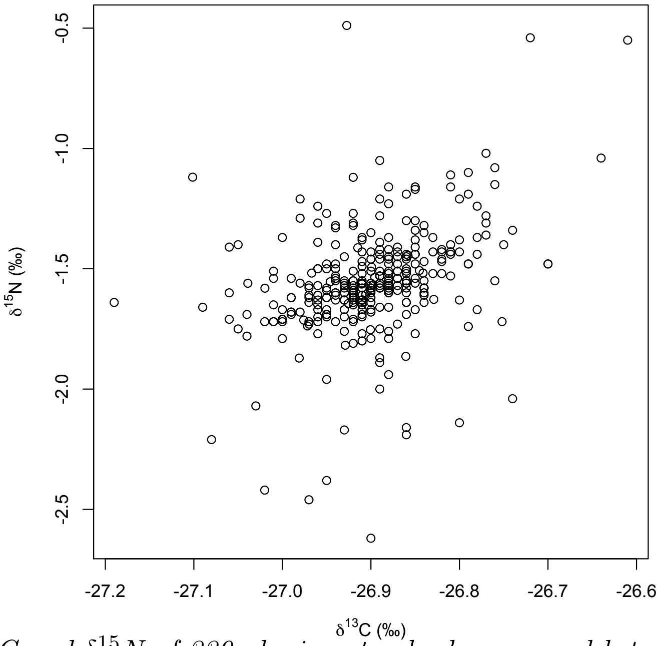

Figure 4.8: *$\delta^{13}C$ and $\delta^{15}N$ of 339 alanine standards measured between 40 different mass spectrometer runs. Data does not include initial burn of alanine, nor does it include the reference alanines which were used to calibrate the measurement software.*

which are labelled 'revised' runs. Figure 4.8 shows variation in δ^{13}C and δ^{15}N of the 339 alanine standards measured between 40 different mass spectrometer runs. Figure 4.9 demonstrates the variation in alanine δ^{13}C and δ^{15}N between runs. Although there is larger variation for earlier runs, there is no systematic deviation from the mean. Since almost all of the samples were analysed in three separate runs the potential effect of any one run is minimized and is taken into account by the cut-off for triplicate reproducibility discussed below.

Powdered bovine liver was used as a secondary standard, and each mass spectrometer run included one or two measurements. Figure 4.10 shows the variation in δ^{13}C and δ^{15}N between runs. From Figures 4.9 and 4.10 it is clear that the first six runs, measured on a different mass spectrometer, are not significantly different from the remainder. There is also an increase in measurement precision of both alanine and bovine liver standards after run GEO02748. This may reflect an improvement in instrumental tuning. GEO runs prior to this have more variable δ^{13}C and δ^{15}N in standards. The standards

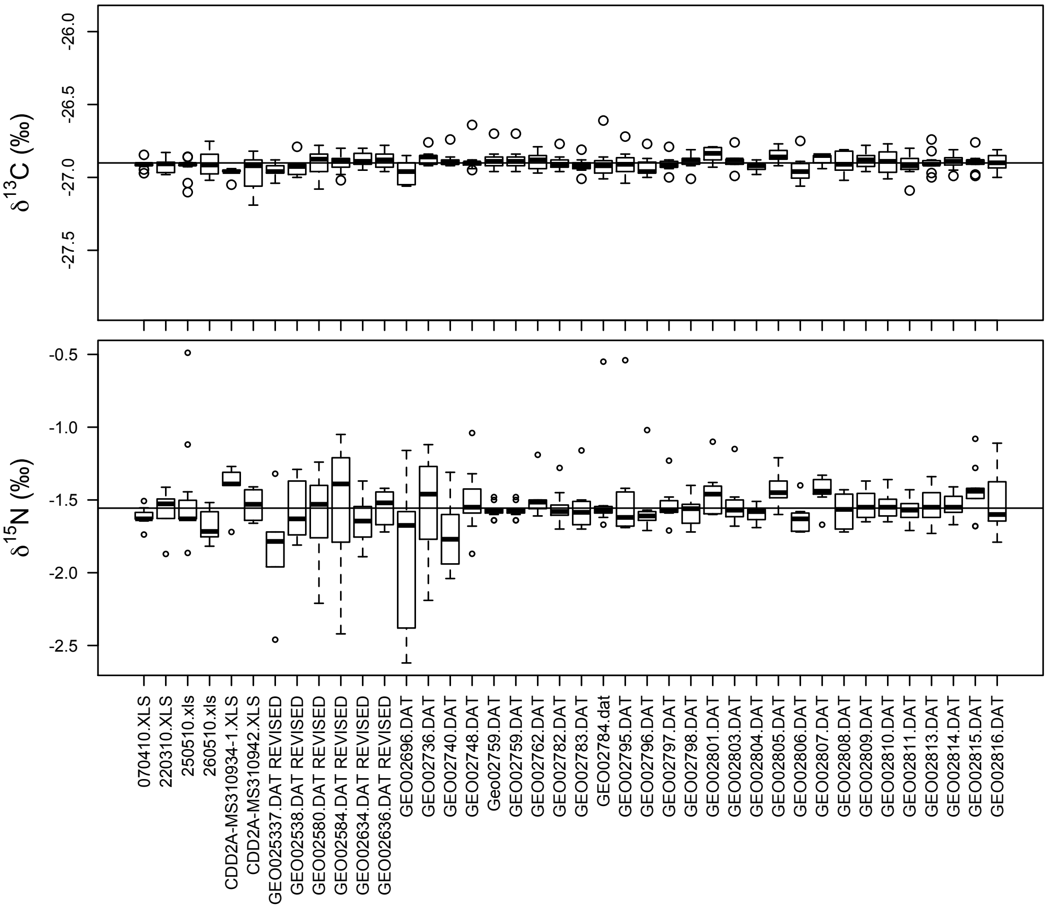

Figure 4.9: *Box plot of* $\delta^{13}C$ *and* $\delta^{15}N$ *of 339 alanine standards measured between 40 different mass spectrometer runs. Data does not include initial burn of alanine, nor does it include the reference alanines which were used to calibrate the measurement software. Mean* $\delta^{13}C$ *and* $\delta^{15}N$ *are shown as a solid line for each graph. 'Revised' runs refer to a recalibration of alanine standard and are plotted as corrected values. Run GEO02696 may have slightly lower than average* $\delta^{15}N$*. The first six runs were measured on a different mass spectrometer from the remainder, but note that there is no significant difference in* $\delta^{13}C$ *and* $\delta^{15}N$ *of alanine.*

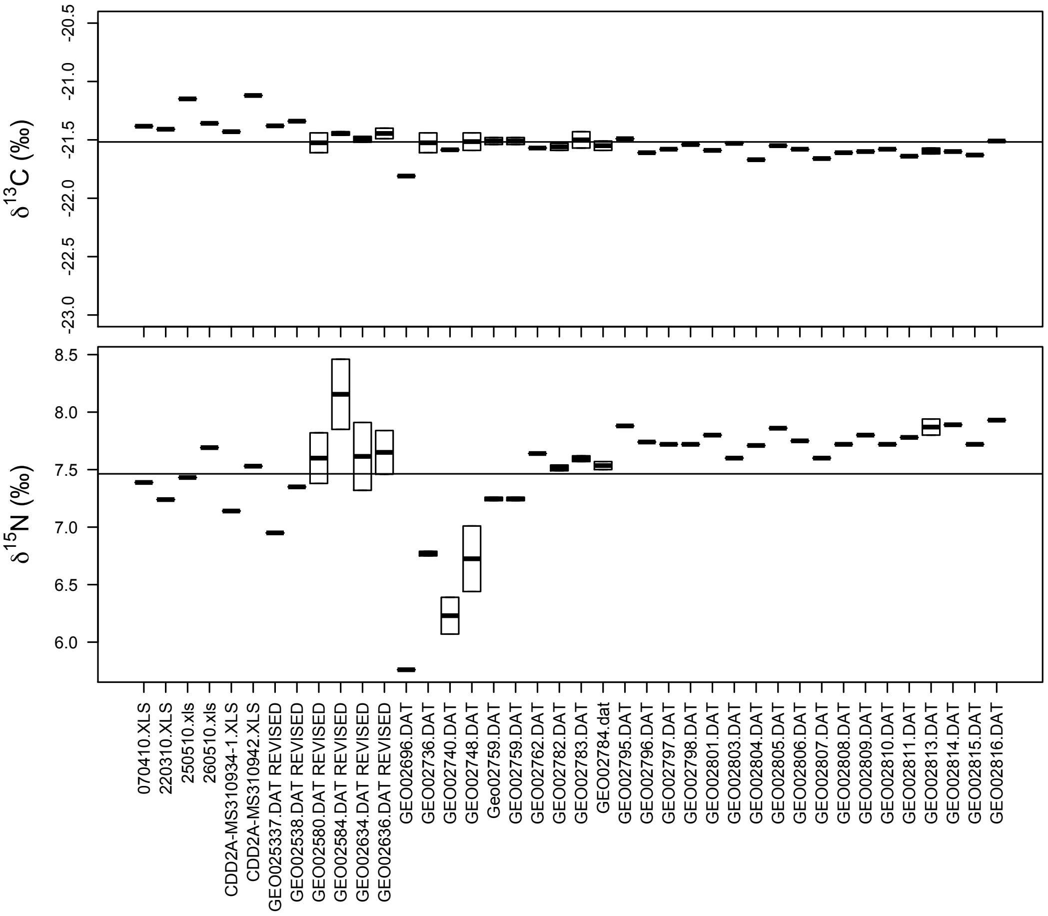

Figure 4.10: *Box plot of $\delta^{13}C$ and $\delta^{15}N$ of secondary standards (bovine liver) measured between 40 different mass spectrometer runs. Mean $\delta^{13}C$ and $\delta^{15}N$ are shown as a solid line for each graph. 'Revised' runs refer to a recalibration of alanine standard and are plotted as corrected values. As for alanine, the single bovine liver standard analysed in run GEO02696 may have slightly lower than average $\delta^{15}N$. The first six runs were measured on a different mass spectrometer from the remainder, but note that there is no significant difference in $\delta^{13}C$ and $\delta^{15}N$ of the bovine liver standard.*

for GEO02696 have lower δ^{15}N than expected. To overcome potential errors, samples were run in triplicate, and averaged values were accepted only if the three runs produced relatively good agreement (see 4.4 below). Any potential anomaly introduced by a slightly unusual run would thus be removed.

4.4 Data quality

Data quality monitoring is important to ensure that no contamination has occurred and to ensure that the collagen is preserved sufficiently to yield meaningful results. Here collagen refers to the substance extracted by the Longin method, which is related to, although not necessarily identical to the collagen protein present in living bone since it may contain non-collagenous bone proteins in small quantities, and since the collagen protein itself may have undergone some diagenetic alterations (DeNiro and Weiner, 1988; van Klinken, 1999). Three tests are routinely applied to make assessments of collagen quality. Due to the high humidity and hot climate of central Italy, collagen preservation was extremely variable and data quality indicators were examined carefully. Originally 542 samples were chosen for analysis, but 112 were rejected due to poor preservation based on these characteristics.

The first metric for collagen preservation is the amount of collagen extracted from the bone, which is based on the mass of collagen extracted by the Longin process compared to the initial starting mass. Early experiments indicated that amino acid profiles of collagen remain consistent until samples are very degraded, with very low collagen yields of between 0.5 and 1 % weight (Beeley and Lunt, 1980). More recent work on artificially and archaeologically degraded collagen shows that the C/N ratio, amino acid composition, bulk δ^{13}C and bulk δ^{15}N remain consistent until collagen yields are less than about 1% weight (Dobberstein et al., 2009). Their study found that after collagen degrades beyond the stability limit, around 1% weight, changes occur rapidly as the collagen mixes with smaller collagen fragments, non-collagenous bone proteins, and other non-protein molecules like lipids. This makes collagen a useful substance to study, where the biogenic effect can be easily distinguished from the diagenetic signal. The average % yield for the accepted samples in this study was $6.24 \pm 3.80\%$, with a range of 1.0% to 22.7%. Figure 4.11 shows that C/N ratio becomes more varied with lower collagen yields. In this study,

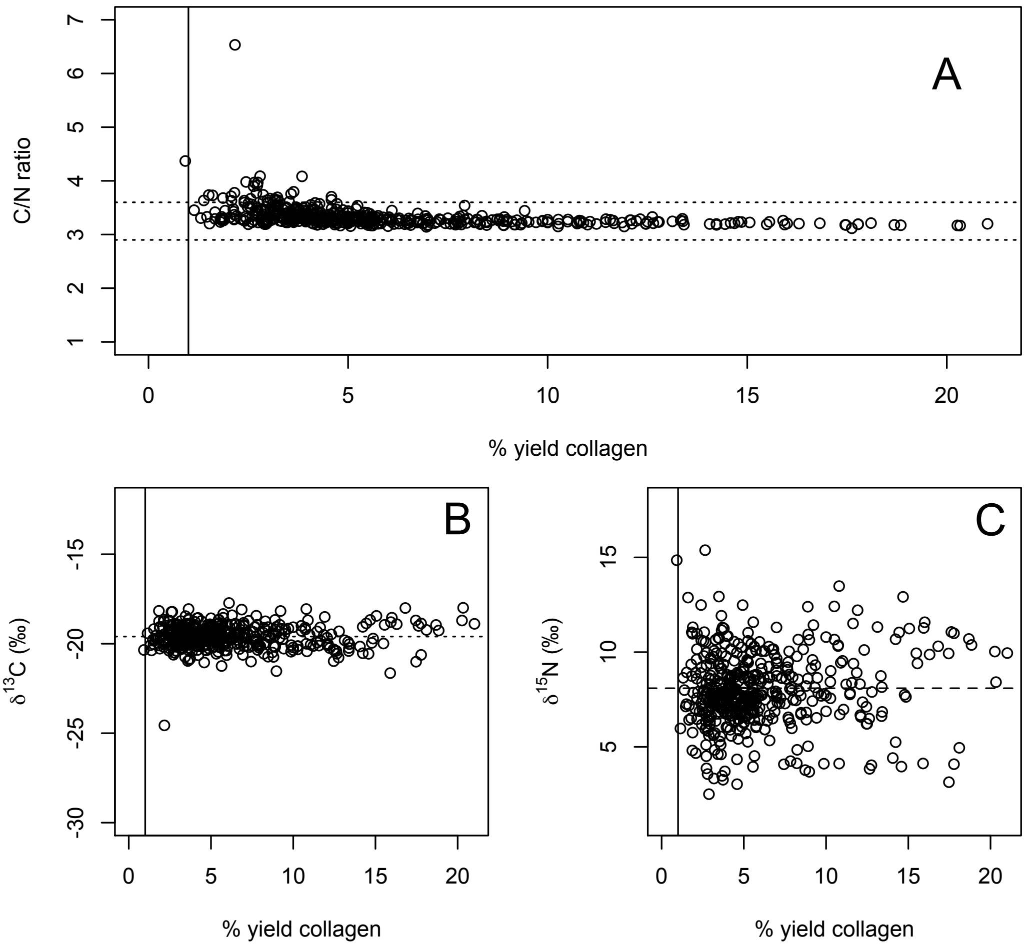

Figure 4.11: *Plot of measured %yield of all analysed samples for A) C/N ratio, B) $\delta^{13}C$ and C) $\delta^{15}N$ for individual (unaveraged) measurements. Vertical line indicates 1% yield. For C/N ratio, dotted lines indicate C/N ratio below 2.9 or above 3.6. For $\delta^{13}C$ and $\delta^{15}N$ dotted line shows the mean value for all measurements. This graphic does not depict VM3592 measurement A (GEO02580) which had a $\delta^{13}C$ of -73.21‰, and was rejected.*

samples with collagen yields less than 1.0% did not yield enough collagen for analysis. Percent yield of collagen can vary widely depending on the method of collagen extraction. Other metrics must be analysed to ensure good preservation and data quality.

Analysis of the % C an % N in extracted collagen is another useful indicator of preservation. Carbon makes up approximately 35% of intact collagen by weight, while nitrogen makes up 11-16% (van Klinken, 1999). The average %C

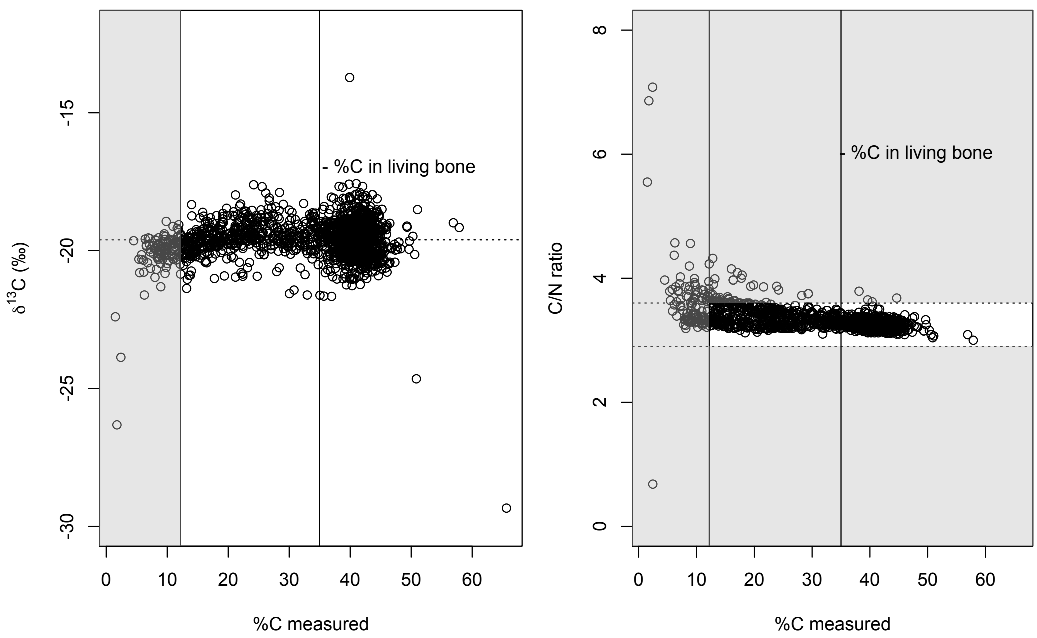

Figure 4.12: *Plot of measured %C for $\delta^{13}C$ and C/N ratio for individual (un-averaged) measurements. For $\delta^{13}C$ dotted line shows the mean $\delta^{13}C$ value for all measurements, while the solid vertical line illustrates the average %C in living bone, as well as the samples with %C lower than* 12.2% *which were rejected. For C/N ratio, the shaded area with %C below 12.2 and with C/N ratio below 2.9 or above 3.6 illustrates measurements that were rejected. This graphic does not depict VM3592 measurement A (GEO02580) which had a $\delta^{13}C$ of* −73.21‰*, and was rejected.*

was $35.4 \pm 10.1\%$, but with a wide range of $12.2 - 48\%$. Figure 4.12 shows that below 12.2%C, both δ^{13}C and C/N ratio become more highly varied and so were rejected. Some samples with %C above 12.2 were rejected if they failed due to other criteria outlined below. The average %N was $12.6 \pm 3.8\%$, ranging from $4 - 18\%$. Samples with measured %C and %N significantly higher than the expected percentages of living bone may be partly due to inaccuracies in measuring the weight of collagen prior to mass spectrometry, since precision was only available to the nearest 10th of a milligram. Figure 4.13 shows that variability in δ^{15}N and C/N ratio increase for samples with %N below 4.[1]

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[1] Note that although the range of δ^{15}N appears similar for samples with %N < 4 as for samples with %N > 12 this is because there are $10x$ more samples with higher %N than lower %N and this reflects the inherent increase in variability as sample size increases.

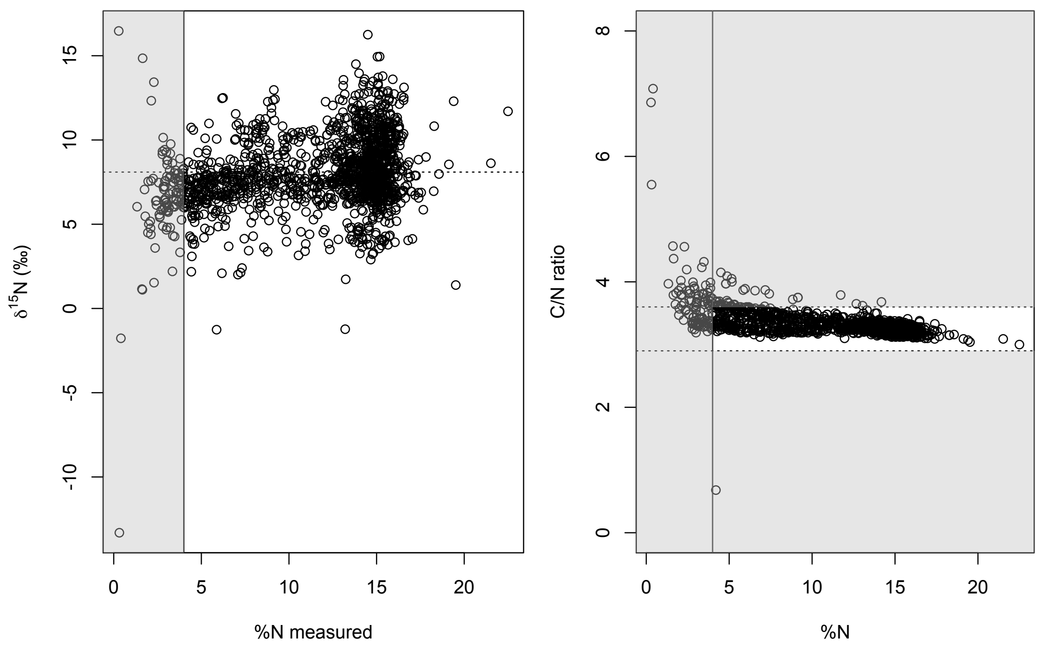

Figure 4.13: *Plot of measured %N for δ^{15}N and C/N ratio for individual (un-averaged) measurements. For δ^{15}N dotted line shows the mean δ^{15}N value for all measurements, while the solid vertical line illustrates the samples with %C lower than 4% which were rejected. For C/N ratio, the shaded area with %N below 4 and with C/N ratio below 2.9 or above 3.6 illustrates measurements that were rejected.*

Similarly %N was not the only criterion for sample acceptance.

The third measure of data quality is the elemental ratio of carbon to nitrogen (C/N ratio). The calculated C/N ratio for living bone collagen based on its amino acid constituents is 3.09. A C/N ratio of 2.9 to 3.6 is often considered acceptable and indicative of well-preserved, uncontaminated collagen (Ambrose, 1990; DeNiro, 1985; Schoeninger et al., 1989). Van Klinken (1999) reports an average C/N ratio of 3.29 ± 0.27 (n=2146) based on results from the Oxford radiocarbon laboratory. C/N ratios may fall outside of this range either due to contamination or due to the effects of collagen degradation. Contamination by plant-derived humic acids, which are comparatively rich in carbon, and low in δ^{13}C (-24 to -22‰) increase C/N while making δ^{13}C more negative. This effect would be larger for low-yield samples, and lower collagen yield samples have a tendency to produce more abnormal C/N ratios (Ambrose, 1990;

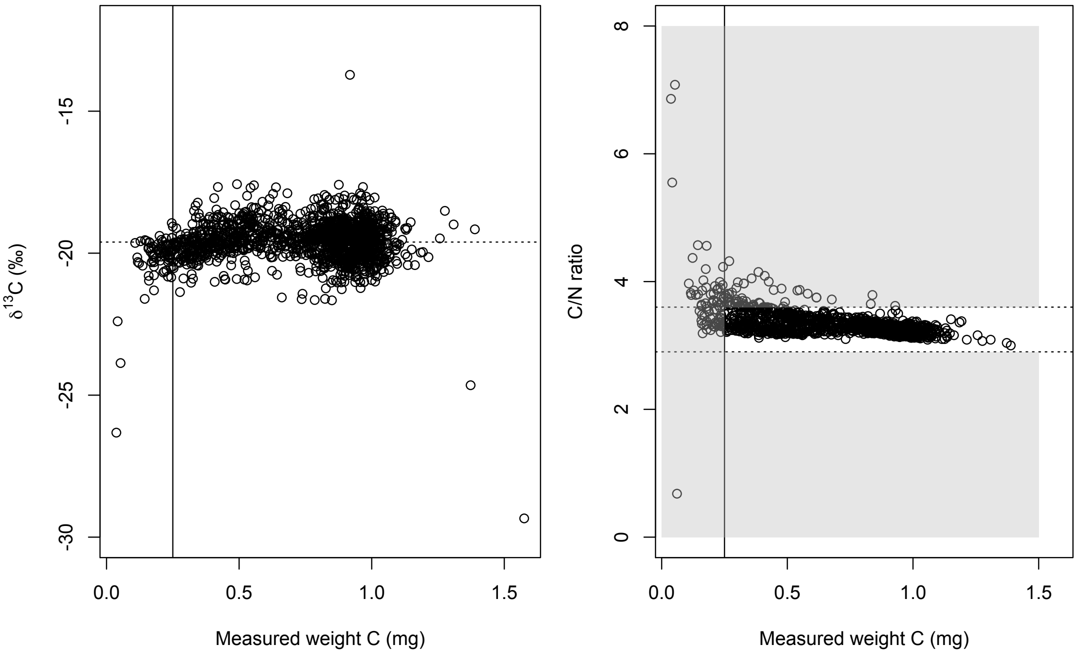

Figure 4.14: *Plot of measured weight of C(mg) for $\delta^{13}C$ and C/N ratio. For $\delta^{13}C$ dotted line shows the mean $\delta^{13}C$ value for all measurements, while the solid vertical line illustrates cut-off point of 0.250mg of measure C. Samples below this were rejected. For C/N ratio, the shaded area with C (mg) below 0.250 and with C/N ratio below 2.9 or above 3.6 illustrates measurements that were rejected. This graphic does not depict VM3592 measurement A (GEO02580) which had a $\delta^{13}C$ of −73.21‰, and was rejected.*

Schoeninger et al., 1989). Most authors expect poorly preserved samples to result in anomalously high C/N and more negative δ^{13}C (Dobberstein et al., 2009; van Klinken, 1999). Higher C/N ratios could also result from the loss of the amino acid glycine, which is easily hydrolised and has a C/N ratios of 2, lower than collagen's average. Although confining the acceptable C/N range has been suggested (van Klinken, 1999) no more precise definition has been adopted. For this study, the average C/N ratio of the accepted samples was 3.28±0.09, with a range of 3.11 to 3.60.

To ensure valid mass spectrometer data, a cut-off for absolute amount of carbon and nitrogen was also established. Samples were rejected with measured

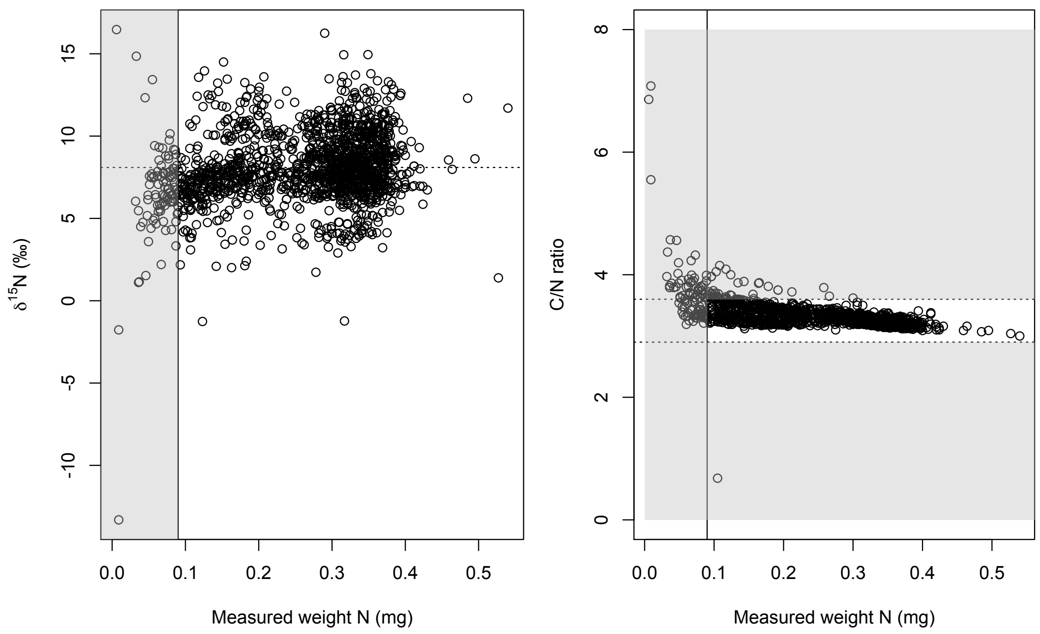

Figure 4.15: *Plot of measured weight of N(mg) for $\delta^{15}N$ and C/N ratio. For $\delta^{15}N$ dotted line shows the mean $\delta^{15}N$ value for all measurements, while the solid vertical line illustrates cut-off point of 0.090mg of measure N. Samples below this were rejected. For C/N ratio, the shaded area with N (mg) below 0.090 and with C/N ratio below 2.9 or above 3.6 illustrates measurements that were rejected.*

Cmg < 0.25 and Nmg < 0.09. Figure 4.14 illustrates how δ^{13}C and C/N ratio are more variable for samples which measured less than 0.250mg C. Figure 4.15 illustrates the same for the nitrogen.

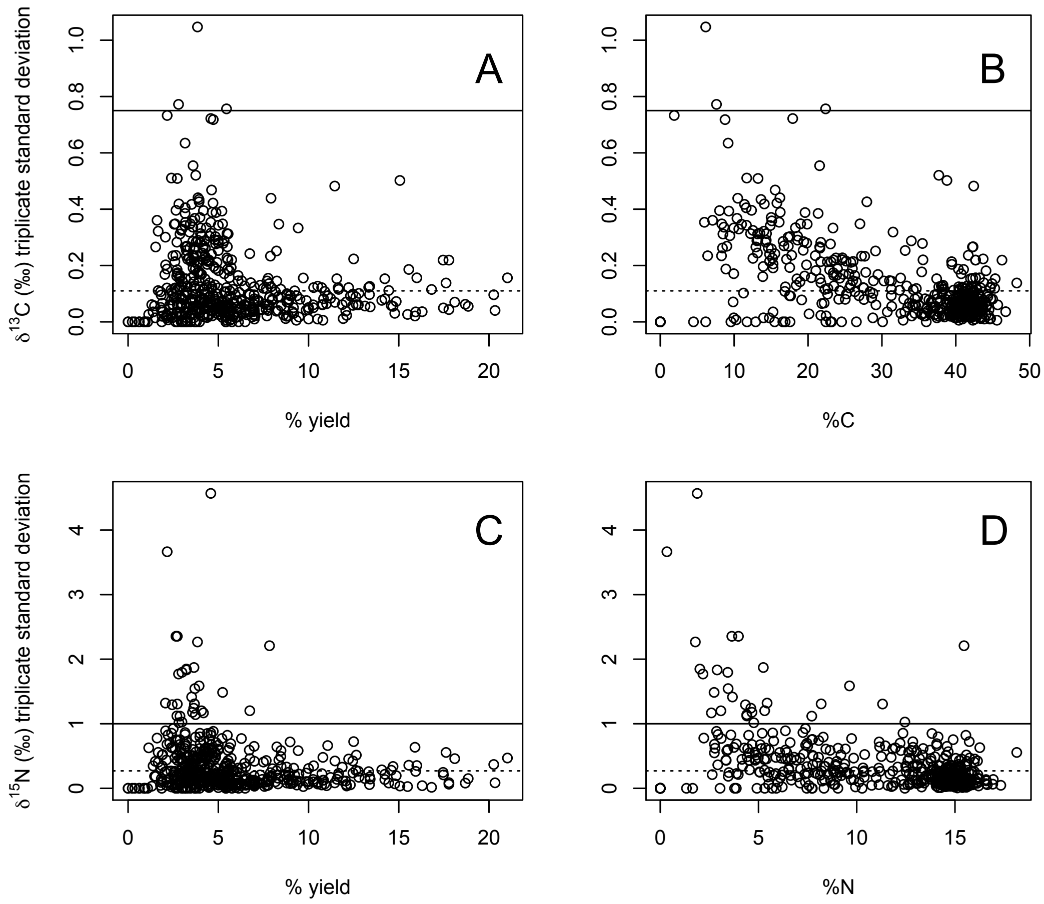

Figure 4.16: *A) Plot of standard deviation of triplicate measurement for $\delta^{13}C$ (A-B) and $\delta^{15}N$ (C-D) for % yield (A and C), %C (B) and %N (D). Dotted line shows average triplicate standard deviation of accepted samples. Solid line shows cut-off value for sample rejection.*

The majority of samples were measured in triplicate, where the extracted collagen was analysed in three separate randomized mass spectrometer runs. Samples were rejected if the three measurements did not closely agree. Samples were rejected if the standard deviation for the triplicate measurements was greater than 0.75‰ for δ^{13}C and 1.0‰ for δ^{15}N. The average reproducibility of the accepted samples was ±0.11 for δ^{13}C and ±0.27 for δ^{15}N. Figure 4.16 illustrates how samples with larger triplicate standard deviations tend to have poorer preservation as measured by percent yield, percent C and percent N.

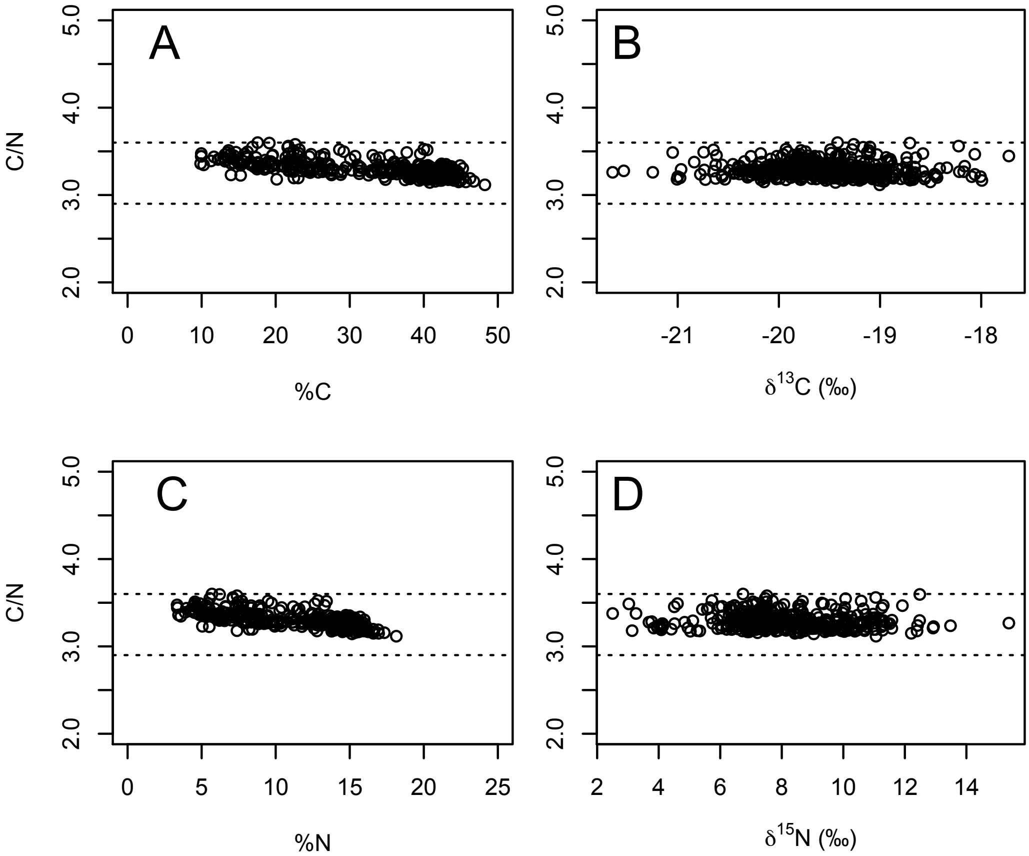

Figure 4.17: *Summary of data quality statistics (C/N, %C, %N, $\delta^{13}C$ and $\delta^{15}N$ for accepted samples. A) C/N vs. %C, B) C/N vs. $\delta^{13}C$, C) C/N vs. %N, D) C/N vs. $\delta^{15}N$.*

A total of 430 samples were accepted based on the criteria discussed above. The information about data quality for the accepted samples is summarized in

Figure 4.17. Note that there is a slight correlation between %C and C/N (Figure 4.17A) and between %N and C/N (Figure 4.17C). This reflects differences in the amount of C and N measured by the mass spectrometer, which appears to measure less than the expected amount of nitrogen relative to carbon for small samples. The isotopic ratios do not appear to be affected (see Figures 4.14 and 4.15 above). Ultrafiltration was determined not to be necessary because separate experimentation confirmed that ultrafiltration did not contribute a significant effect to δ^{13}C and δ^{15}N of collagen extracted from poorly preserved bone (Nitsch and Hamilton unpublished data). Data of comparable quality to ultrafiltered samples can be obtained by paying strict attention to the other quality criteria discussed above. Omitting the extra expense of ultrafiltration allowed a larger number of samples to be analysed.

4.5 Meta-analysis: methods for data collection and analysis

The second aim of this study was to understand the results from Italy within a wider European and Mediterranean context. This was accomplished by undertaking a meta-analysis of previously published data. I collected the results of stable isotope analysis (δ^{15}N and δ^{13}C) from 121 published collections of human and animal results from Europe and the Mediterranean, from the Roman to Late Medieval periods. The δ^{13}C and δ^{15}N for each individual was recorded, along with information about the species, age and sex, where available. Data from over 3500 individuals were analysed, including 600 animals. Date categories were R (Roman, AD 1-500), EM (Early Medieval, AD 500-1000) and LM (Late Medieval AD 1000-1500). Age categories are A (16+), J (2-16) and I (< 2). When age was given as a range (e.g. 1-3 years) the age was taken as a median, with any individual approximately near 2 years treated as an infant to ensure that juveniles were not biased by a potential breastfeeding signal. Sex was recorded as M or F when given, including unclear sexes (M?, F? etc.).

Coastal sites were those sites within a 10km straight line distance from the coast.

In cases where there were *a priori* reasons to subdivide a site (for example, the division between monastic and lay burials at Whithorn; Müldner et al., 2009) these divisions were maintained in the database as two separate sites. At Medieval Norwich (Bayliss et al., 2004) the radiocarbon dates provided with the stable isotopes were partially before and partially after AD 1000. The mean date estimate, not the error range, was used to determine whether the individual was EM or LM. Zaragoza Predicatores (Mundee, 2010) had a date range of 9th to 12th century and was treated as EM. The Ibiza Late Antique group (Fuller et al., 2010) had a date of 4th to 7th century and was treated as EM. The single infant individual from the Christian Catacombs of St Callixtus (Rutgers et al., 2009) was not considered. Determining coastal or inland status was difficult for sites on estuaries and river deltas. Antwerp and Gloucester were both considered coastal. Individual data points from Wharram Percy (Richards et al., 2002), Castro dei Volsci, Rome Cancelleria (both Salamon et al., 2008), Naples and Florence (both Fornaciari, 2008) were all estimated from figures.

The sites have been divided into four geographical regions: the Mediterranean, Central Europe, Northern Europe and England. In order to compare inland and coastal sites, I defined any site within 10km of the sea as ‘coastal’. The ‘Mediterranean Region’ includes all sites in Spain and sites as far south as Leptiminus in Tunisia. The Dakhleh Oasis (Dupras and Schwarcz, 2001) in Egypt is far enough south that its arid environment constitutes a unique isotopic system. At the Dakhleh Oasis, the extremely high δ^{15}N values in the humans (17.9‰) corresponded to the high δ^{15}N of the contemporary fauna (14‰; Dupras et al., 2001; Dupras and Schwarcz, 2001). The Early-to-Late Medieval site of Ridanas, Sweden (Kosiba et al., 2007) exhibited unusually high δ^{13}C ratios in animals, as well as humans, and was not considered in the meta-analysis. The large number of sites from Britain, and specifically England, has allowed me to treat this area as a separate region. Only English sites were included in the analysis, since British sites outside of England may have an unusual diet that would skew the results of the meta-analysis. Orkney has been well-studied (Barrett et al., 2001; Richards et al., 2006), but its unique ecological system has resulted in a diet with a reliance on large amounts of fish.

4.5.1 Selection of faunal samples for meta-analysis

As discussed in Chapter 3, isotopic ratios can vary widely for reasons other than diet. Climate, geography and inter-individual variation are some of the many non-dietary factors that can affect isotopic ratios. Because of this uncertainty, it is difficult to reconstruct meaningful dietary information from a single individual. Comparing differences between larger populations is advantageous because it can limit the uncertainty caused by inter-individual variation. On the other hand, examining differences and similarities between different populations is fraught with other problems of comparability, since both anthropogenic and non-anthropogenic factors can influence stable isotope ratios. One of the goals of the meta-analysis was to examine environmental and geographic variations in δ^{13}C and δ^{15}N by reconstructing a 'faunal baseline' where possible.

Ideally one would reconstruct the δ^{13}C and δ^{15}N at the base of the food-chain from plants undergoing photosynthesis and fixing nitrogen, directly or indirectly. Plant remains survive poorly on archaeological sites, and recovering a representative biogenic isotopic signature is difficult. For this reason, measuring the isotopic ratios of local, contemporary herbivores is often the best solution, since they can be assumed to reflect the average δ^{13}C and δ^{15}N that would be available to the human population.

The unknown amount of uncertainty in the measurement of the faunal baseline makes this relationship difficult to assess. The choice of which samples to include in the so-called 'faunal baseline' for a site can raise many problems.

Choosing an appropriate faunal assemblage from a nearby site can also introduce error, a problem encountered by Mundee (2010) in her analysis of Medieval Spanish diets. No faunal samples were recovered from the site of Jaca to provide a comparison to the humans. The two nearest faunal assemblages at Huesca and Barbastro (70 and 120km away) were extremely different from one another in δ^{13}C and δ^{15}N, making the estimation of a plausible human-faunal isotopic enrichment relationship difficult.

Establishing a faunal baseline would allow intra-site human-faunal Δ^{13}C and Δ^{15}N trophic level relationships to be calculated. However, the assumption that human isotopic values are related to faunal isotopic values is not straightforward. Some of the problems of assuming that the plant δ^{15}N available to an animal would be identical to the plant δ^{15}N available to a human are outlined in Hedges and Reynard (2007). Animals may be extremely selective in the types of plants they consume or the parts of plants they consume. Animals, even domesticated species, can also dwell in different niche ecosystems apart from humans, such as pigs in forested areas or sheep grazing on salt marshes. Manuring could also affect the δ^{15}N ratio of plants, and if humans were fed manured crops where animals were not, it would also result in a difference in baseline offset between humans and animals (Bogaard et al., 2007). Some animals could have been young enough when they were slaughtered for food to retain a nursing signal.

It was possible to reconstruct human-animal isotopic comparisons for 64 of the human collections in the meta-analysis. The average human δ^{13}C and δ^{15}N was compared to the weighted mean of sheep/goat, pig and cattle samples from the same site or from a nearby site where possible. The details of this analysis are presented in 6.3. In 7.1.1 I examine the problems in reconstructing a human-faunal trophic relationship on the basis of δ^{15}N in more detail. Marine fish were also included where available in order to compare variability between geographic regions. By quantifying some of the complicating factors discussed above, I attempt to calculate a more accurate estimate of the amount of animal protein in the Roman and Medieval diet.

4.5.2 Statistical Methods

Statistical analysis of the data was based on multivariate linear modelling. The hierachical structure of the data was essential to consider, namely the fact that individual data points were clustered within sites, within regions. The possibility that individuals from one site were more likely to be similar to each than to individuals from another site needed to be accounted for. Failing to incorporate the site-based structure of the data is unsatisfactory and misleading. Analysis based on site averages will fail to account for differences in indivdual-level variables such as age or sex that may vary between sites. Therefore, I applied a multi-level model (also known as a hierachical linear model) to quantify the significance of different effects at different levels. Two individual multi-level models were applied, for each δ^{13}C and δ^{15}N using the R programming language (version 2.15.0). Variance was estimated using a Restricted Maximum Likelihood estimate (REML). The model calculates linear regression for the measured variable (δ^{13}C or δ^{15}N) fitted to the estimates (and uncertainty) of the various explanatory factors included (i.e. Age, Sex, Date etc.), but also fitted to the estimate (and uncertainty) for the average of the grouping variable (i.e. Site). In this way the significance of multiple different effects on δ^{13}C and δ^{15}N can be accurately determined. Results are reported as significant where $p < 0.05$, however some moderately significant trends ($0.05 \leq p < 0.1$) are also mentioned.

4.6 Summary

This chapter has summarized the material chosen for isotopic analysis in central Italy. The selection of sites for new analysis was designed to provide new information about previously unstudied types of sites—especially inland, rural locations. The analytical methods described how several measures of data quality were taken, and how data from collagen samples was screened prior to being included in the analysis. The results of these new isotopic analyses is described in Chapter 5. The final portion of this chapter described how the results from central Italy would be combined with a meta-analysis of all previously-published data from Roman and Medieval Europe. Data from Roman, Early and Late Medieval periods was collected from four different geographic regions. Faunal samples were also included in the meta-analysis to provide an environmental baseline reconstruction. The results of the meta-analysis are presented in Chapter 6.

5

Results of stable isotope analysis of humans and fauna from Roman and Medieval central Italy

This chapter presents the results of the stable isotopic analysis of the 369 new analyses undertaken from central Italy. This includes 254 adults, 63 juveniles and 51 infants (plus 1 individual of indeterminate age) from eight different sites. The full list of results is presented in Appendix A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, and A.9. First, I describe the results of the faunal samples recovered from Villamagna, in comparison to previously published faunal results from the rest of Italy. The large degree of inter-individual variation in fauna relative to inter-site variation does not provide any evidence for large-scale geographic effects within Italy.

Next, the new human isotopic results are presented and compared to results from eight previously published sites from Italy dated c. AD 1–1500. The Roman Italian sites are presented first: Palestrina, Pompeii, Casale del Dolce, and Osteria della Fontana. These are compared to the previously published sites of ANAS (Prowse et al., 2004), Isola Sacra (Crowe et al., 2010; Prowse et al., 2004), Velia (Craig et al., 2009) and the Early Christian individuals from the catacombs of St Callixtus (Rutgers et al., 2009). Then the results from the Early Medieval sites of Marcellino e Pietro and Esanatoglia are discussed. These are compared to the previously published sites of Castro dei Volsci (Salamon et al., 2008), and the catacombs of St Callixtus. Finally the results from the Medieval monastery of Villamagna are presented. This site is compared to the Late Medieval results from the Palazzo della Cancelleria (Salamon et al., 2008), and the aristocratic individuals from Florence and Naples (Fornaciari, 2008). This group of 16 Italian sites is a subset of the overall European data, discussed in Chapter 6. For each individual, the following information was recorded: δ^{13}C, δ^{15}N, Species, Sex (M, F or U), and Age (A, J, I). Individuals were also divided into one of three chronological periods: R (AD 1–500), EM (AD 500–1000) and LM (AD 1000–1500). Sites were overall described as Coastal (C) if they were 10km direct distance from a saltwater coast, or Inland (I). For every site except Villamagna, all individuals were given the same date code. At Villamagna the majority of the individuals were LM, although a few were EM. For Villamagna, additional information about the burials was known, such as phasing, body position and grave goods. In addition to being considered as one of the Italian sites, the intra-site differences within Villamagna were examined separately.

Because of expected isotopic differences between adults and infants, the examination of inter-site differences was restricted to adults only. Statistical differences between individual pairs of sites were calculated using an analysis of variance test, but with a post-hoc correction applied using the Tukey Honestly Significant Difference test. The size and significance of site-based pairwise comparisons at the 95% confidence interval referred to in the text are summarised in Table B.1 for δ^{13}C and B.2 for δ^{15}N in the Statistical Appendix (B).

Inter-site differences were large, with the majority of sites being statistically distinct in either δ^{13}C, δ^{15}N or both. This site-level variability needed to be accounted for in order to investigate chronological differences. A mixed multilevel model was used, treating δ^{13}C and δ^{15}N separately, with Coastal/Inland, Sex, and Datecode as explanatory variables. The same procedure was followed as described in Section 4.5.2 above. The site-level variation was treated as a random effect. The results of this Italian model, and an examination of the effects of coastal proximity, sex, and date for Italian sites, are discussed at the end of this chapter.

5.1 Faunal isotopic ratios

The faunal samples analysed from Villamagna include remains from the Roman and Late Medieval phases (12th-15th century AD). A total of 29 individuals were analysed, including ovicaprids, pigs, cattle and horses (see Table 5.1). It was estimated (J. Hamilton, pers. comm.) that all individuals chosen for isotopic analysis were adults and it is not expected that their isotopic ratios are influenced by the effects of milk consumption in infancy. The average δ^{13}C was -20.5 ± 0.6‰, ranging from -21.6‰ to -18.4‰. Nitrogen isotopic ratios averaged 4.4 ± 1.0‰, ranging from 2.5‰ to 6.7‰. I use the label 'domesticated herbivores' to refer to results from ovicaprids, cattle and pigs, although pigs may consume an omnivorous diet. The cattle have a large range in δ^{13}C, which is due to one individual (VMA 15) from context 7525, dated from AD 1150 to 1250 with a δ^{13}C value of -18.4‰. This isotopic ratio is consistent with a diet containing a small proportion of C4 plants, such as millet or sorghum, but may also relate to small-scale climatic variability. The other two individuals sampled from the same context have δ^{13}C values of -20.0‰ and -20.2‰, which is consistent with a C3 diet. Overall, however, there were no significant differences between species (multivariate ANOVA for δ^{13}C and δ^{15}N modelled against species, $p = 0.3544$). There were also no significant differences between the four faunal samples of Roman date, and those from the Late Medieval

Table 5.1: *Summary of isotopic results for faunal samples from Villamagna*

Species	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Bos	7	-20.2	0.9	-18.4	-21.3	4.7	0.9	5.9	3.8
Equus	2	-20.6	0	-20.6	-20.6	4.1	0.1	4.1	4.0
Ovicaprid	10	-20.8	0.7	-19.2	-21.6	4.6	1.1	6.7	3.1
Sus	10	-20.6	0.4	-20.0	-21.1	4.1	0.9	5.3	2.5
Total	29	-20.54	0.64	-18.41	-21.64	4.4	0.96	6.72	2.5

All values ‰

Table 5.2: *Summary of isotopic results for faunal samples from Villamagna by period*

Phase	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Roman	4	-20.3	0.8	-19.2	-21.0	5.1	0.9	6.2	4.1
AD 1100-1350	25	-20.6	0.6	-18.4	-21.6	4.3	0.9	6.7	2.5

All values ‰

period (multivariate ANOVA for δ^{13}C and δ^{15}N modelled against phase, $p = 0.2702$). See Table 5.2.

The average δ^{13}C and δ^{15}N ranges reported from Villamagna are typical of Italian domesticated herbivore isotopic results from previously published studies from the Bronze Age and Roman periods (Craig et al., 2009; Prowse et al., 2004; Tafuri et al., 2009), see Figure 5.1. It should be noted that although it is assumed that only adult individuals were sampled, this is not always specified and the influence of infant diet could affect the variability in isotopic ratios observed here. Although faunal δ^{13}C and δ^{15}N are higher at Isola Sacra compared to Villamagna and Velia, the small sample sizes and large amount of inter-individual variation mean there are no significant differences between these sites (p ranges from 0.13 to 0.94). However, domesticated herbivores from Villamagna, Velia and Isola Sacra differ significantly from the average stable isotope ratios of six unidentified faunal fragments from Etruscan (8th-3rd century BC) contexts reported from Pontecagnano, near Salerno, by Scarabino et al. (2006). The authors of that study suggested the faunal fragments may have been horses, but the average δ^{13}C is significantly lower than other Italian

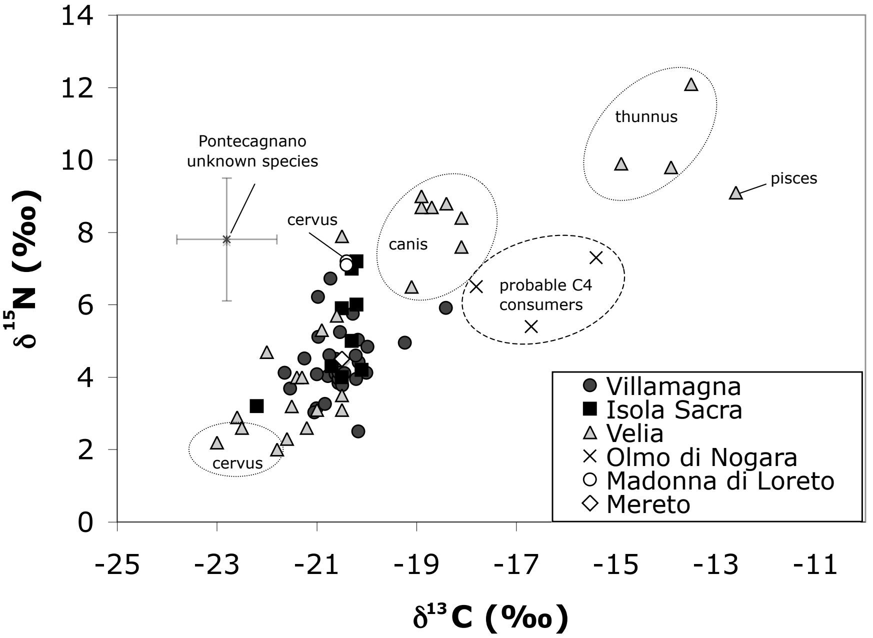

Figure 5.1: *Stable isotope ratios ($\delta^{13}C$ and $\delta^{15}N$) of animal specimens from Villamagna and previously published Italian sites. Domesticated herbivores (ovicaprids, cattle, and pigs) are plotted, along with horses. Other species are plotted as indicated. Data from Velia is from Craig et al., 2009, Olmo di Nogara, Madonna di Loreto and Mereto are from Tafuri et al., 2009. Pontecagnano is from Scarabino et al., 2006. Isola Sacra faunal data is from Prowse et al., 2004.*

sites (-22.8 ± 1.0‰) and the δ^{15}N is significantly higher (7.8 ± 1.8‰) than what would be expected for horses. These results are so dissimilar to other reported Italian results that it is impossible to include them with confidence in an aggregated assessment of ancient Italian isotopic variation. The previously published results from Velia and Isola Sacra (Craig et al., 2009; Prowse et al., 2004) bracket the location of Pontecagnano and do not display evidence of geographic effects which could explain the difference between Pontecagnano and other studies. Excluding the Bronze Age northern Italian C4-feeders (Tafuri et al., 2009), the remainder of the domesticated herbivores (pigs, ovicaprids and cattle) from Italy c. 16th century BC to 15th century AD show a large range but one that is similar between sites (see Figure 5.2). For this study, a typical ancient Italian domesticated herbivore range may be defined on the basis of

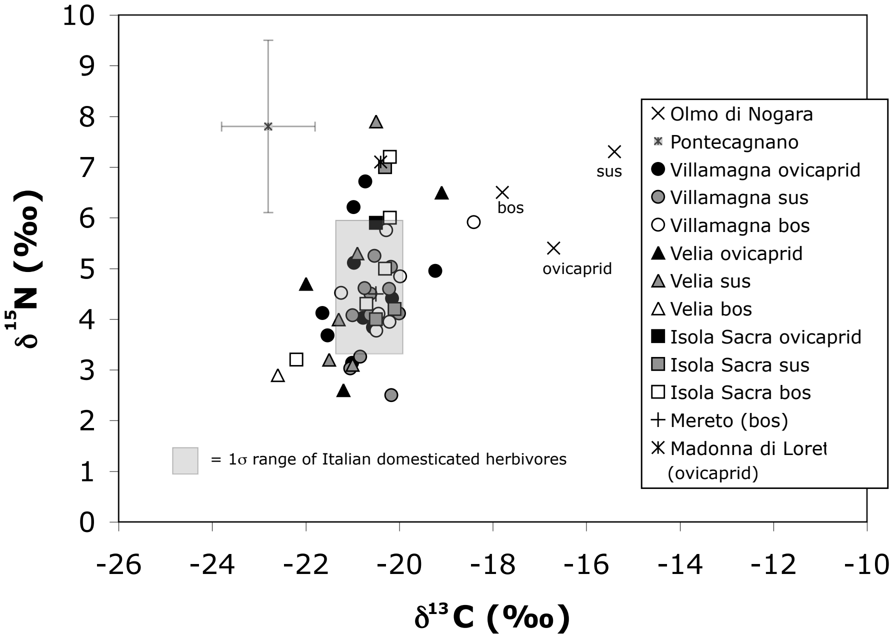

Figure 5.2: *Stable isotope ratios ($\delta^{13}C$ and $\delta^{15}N$) of domesticated herbivore, plotted by species (ovicaprids, cattle and pigs), from Villamagna (this study), Olmo di Nogara, Mereto, Madonna di Loreto (Tafuri et al., 2009), Velia (Craig et al., 2009) and Isola Sacra (Prowse et al., 2004). The 1σ range of Pontecagnano (Scarabino et al., 2006) is also shown. The 1σ range of the average of all domesticated herbivores (excluding Pontecagnano and the C4 consumers from Olmo di Nogara) is shown in the shaded region.*

the 44 specimens from Roman and Medieval contexts, reported here and in previous studies, with δ^{13}C from -21.4 to -20.0‰ and δ^{15}N from 3.3 to 5.9‰. For this group of 44 sheep/goat, cattle and pigs from Italy (including the new data from Villamagna) there is a moderately significant correlation between δ^{13}C and δ^{15}N (Pearson's $r = 0.47$, $p = 0.001$). If this relationship is treated as a linear regression, the slope of the relationship is 0.83, the relative increases in δ^{13}C and δ^{15}N are approximately equal. This correlation is discussed in more detail below.

Table 5.3: *Summary of results from Roman Italian sites*

Site	Age	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Palestrina										
	Adults	5	-19.45	0.24	-19.09	-19.66	9.94	1.11	11.51	8.7
	Juveniles	4	-20.06	0.57	-19.29	-20.65	8.96	1.16	10.66	8.1
Osteria della Fontana										
	Adults	14	-19.72	0.34	-19.02	-20.14	7.68	1.5	11.58	5.73
Pompeii										
	Adults	22	-18.89	0.37	-17.99	-19.48	10.33	0.79	12.4	8.42
Casale del Dolce										
	Adults	59	-20.01	0.45	-18.55	-20.74	7.95	1.42	12.41	5.7
	Infants	7	-19.74	0.8	-18.22	-20.38	8.29	3.34	15.38	6.38
Civitanova Marche										
	Adults	21	-19.6	0.62	-18.06	-20.19	9.45	1.3	13.48	7.21
	Juveniles	8	-19.64	0.54	-18.5	-20.25	9.72	1.37	12.21	8.39

All values ‰

5.2 Roman sites

Chapter 4 described the nature of the isotopic evidence from previously published sites in Roman Italy. This includes two analyses of coastal populations (Isola Sacra and Velia), one population from an early Christian catacomb in Rome, and one cemetery near Rome (ANAS). The sites studied here were chosen to provide a better understanding of Roman diet by analysing individuals from inland areas and by incorporating all results into an overall picture of Roman Italian diet. Here I report the isotopic results from Palestrina, Pompeii, Casale del Dolce and Civitanova Marche. These results are summarized in Table 5.3.

5.2.1 Palestrina

A total of five adults and four juveniles were analysed from the 4th–3rd century BC contexts at Palestrina, an inland, urban site located south-east of Rome. The average adult isotopic ratios from Palestrina are $\delta^{13}\text{C} = -19.4 \pm 0.2$‰ and $\delta^{15}\text{N} = 9.9 \pm 1.1$‰. The δ^{13}C is consistent with a terrestrial diet, but the δ^{15}N

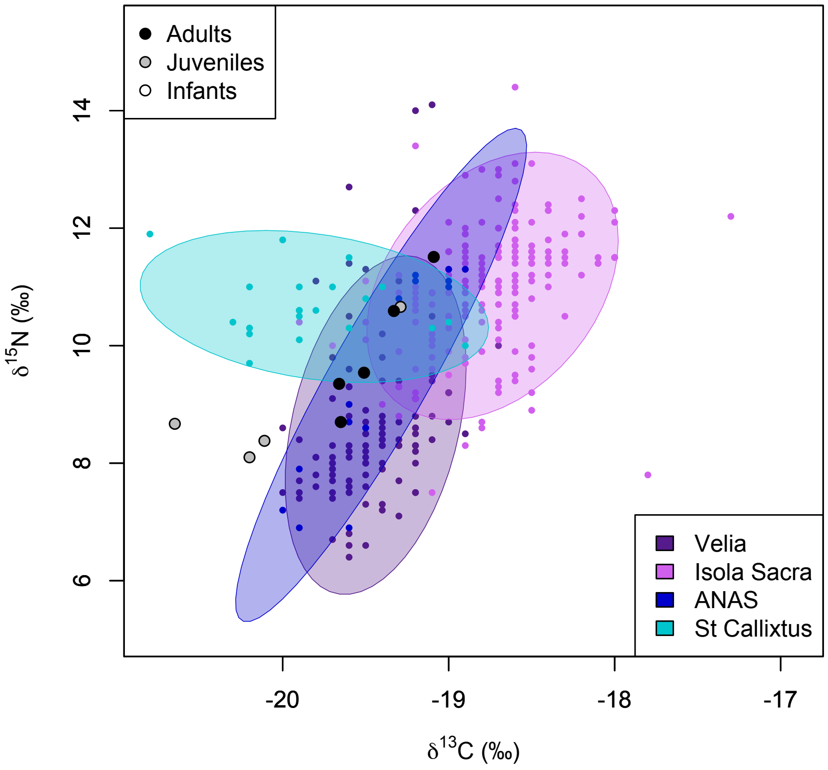

Figure 5.3: *Plot of human $\delta^{13}C$ and $\delta^{15}N$ from 5th-4th century BC Palestrina. Previously published results from Velia (Craig et al., 2009), Isola Sacra (Prowse et al., 2004; Crowe et al., 2010), St Callixtus Catacombs, Rome (Rutgers et al., 2009) and ANAS (Prowse et al., 2004) are also shown. The 90% confidence region for each site is shown as a shaded ellipse.*

values show a large range between the lowest value of 8.7‰ and the highest value of 11.5‰. The correlation between δ^{13}C and δ^{15}N for the five adults at Palestrina is strong and positive (Pearson's $r = 0.97$, $p = 0.006$).

The results from Palestrina are consistent with previously published data from coastal Roman sites (see Figure 5.3). Isotopic results for adults from Palestrina are statistically indistinguishable from results from ANAS (Prowse et al., 2004), the catacombs of St Callixtus (Rutgers et al., 2008), Civitanova Marche, Esanatoglia, Marcellino e Pietro, Pompeii, Rome Palazzo della Can-

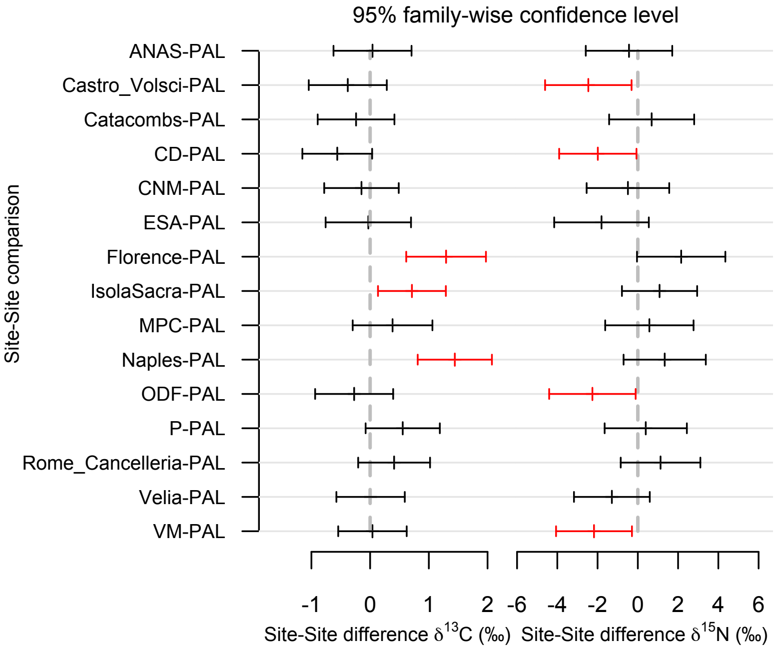

Figure 5.4: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and Palestrina, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Palestrina are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

celleria (Salamon et al., 2008) and Velia (Craig et al., 2009) (p range from 0.06 to 1 for δ^{13}C and δ^{15}N). Differences between Palestrina and other sites are significant (with p values less than 0.05) for δ^{13}C and/or δ^{15}N. For details, see Appendix B.1 and B.2.

The four juveniles from Palestrina have not been precisely anthropologically aged, but fall between the ages of 4 and 16, and so are old enough that a weaning signal is not a potential factor to consider. The average juvenile δ^{13}C value is -20.1 ± 0.6‰ and the average δ^{15}N value is 9.0 ± 1.2‰. This is largely due to one juvenile (PAL3) with much higher δ^{13}C (-19.3‰) and δ^{15}N (10.6‰, see Figure 5.3). The other three juveniles have isotopic ratios significantly lower than the adults.

5.2.2 Pompeii

The results from the 22 adults analysed from Pompeii have a relatively uniform distribution (see Figure 5.6). The mean δ^{13}C was -18.9 ± 0.4‰ and the mean δ^{15}N was 10.3 ± 0.8‰. When the results are plotted alongside the previously published Roman sites, it is clear that the results from Pompeii overlap the results from Isola Sacra and the high δ^{15}N group from Velia. The average δ^{15}N of Pompeii is 1.7‰ higher than Velia ($p < 0.001$, see Figure 5.5). Individuals from Pompeii are very similar to individuals located in or near Rome: the individuals from Pompeii have indistinguishable δ^{13}C and δ^{15}N from Isola Sacra, Marcellino e Pietro, Palestrina and Rome Palazzo della Cancelleria (p from 0.16 to 1.0 for both δ^{13}C and δ^{15}N). Statistical tests are based on Tukey HSD post-hoc corrected 95% confidence estimates. For details see B.1 and B.2.

Two individuals (PF25 and P19) have relatively high δ^{13}C, both -18.0‰, which is more than two standard deviations above the mean for this site. In the case of P19, δ^{15}N is only moderately elevated at 10.3‰ (average for the site) while PF25 is clearly unusual, with an extremely low δ^{15}N value of 8.4‰, which is more than two standard deviations below the mean for the site. Largely due to this individual, Pompeii is one of the few sites where there was no significant correlation between δ^{13}C and δ^{15}N. Sex was known for seven individuals from this site: four females and three males (see Table 5.4). Although the four females have slightly lower δ^{13}C and δ^{15}N than the males, the small sample size means this difference is not statistically significant (two-tailed t-test p values are 0.5420 and 0.6701 for δ^{13}C and δ^{15}N).

A further 31 individuals were previously analysed from Pompeii in an unpublished study, from which the means, standard deviations and ranges have been obtained (Pate, pers. comm.). The results of Pate's analysis of Pompeian

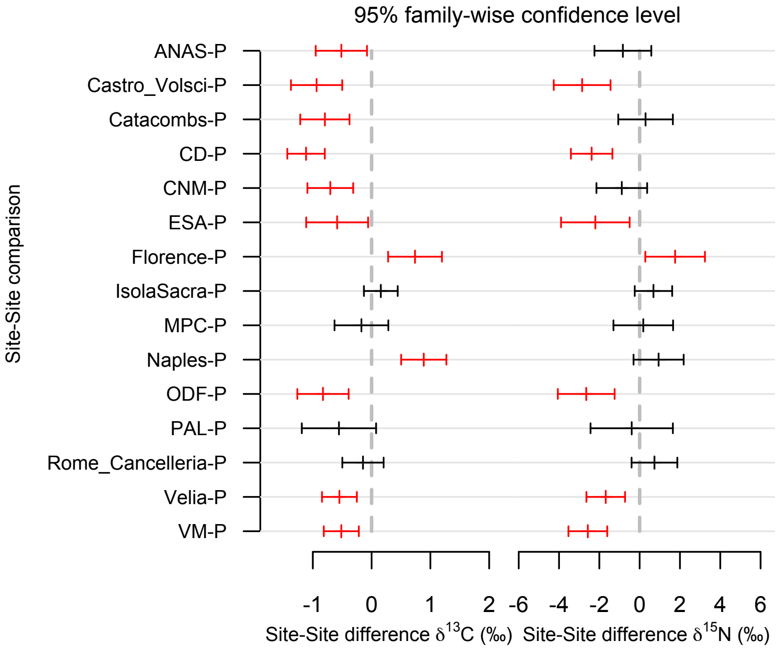

Figure 5.5: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and Pompeii, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Pompeii are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

individuals are significantly different from the results presented here. Pate's male δ^{13}C for 12 individuals is -17.9 ± 1.9‰, with the highest δ^{13}C at -14.4. This is the highest δ^{13}C value ever reported for a human from Italy. Compared to the results from Pompeii presented here, the difference in δ^{13}C is statistically significant (two-tailed t-test $p = 0.0223$), as is the difference in δ^{15}N (two-tailed t-test $p = 0.0160$). Females from Pate's study are also significantly lower in δ^{15}N than in this study (mean $= 9.4 \pm 1.4$‰, two-tailed t-test $p = 0.0141$). There is no significant difference in δ^{13}C (mean $= -19.1 \pm 0.8$‰ two-tailed

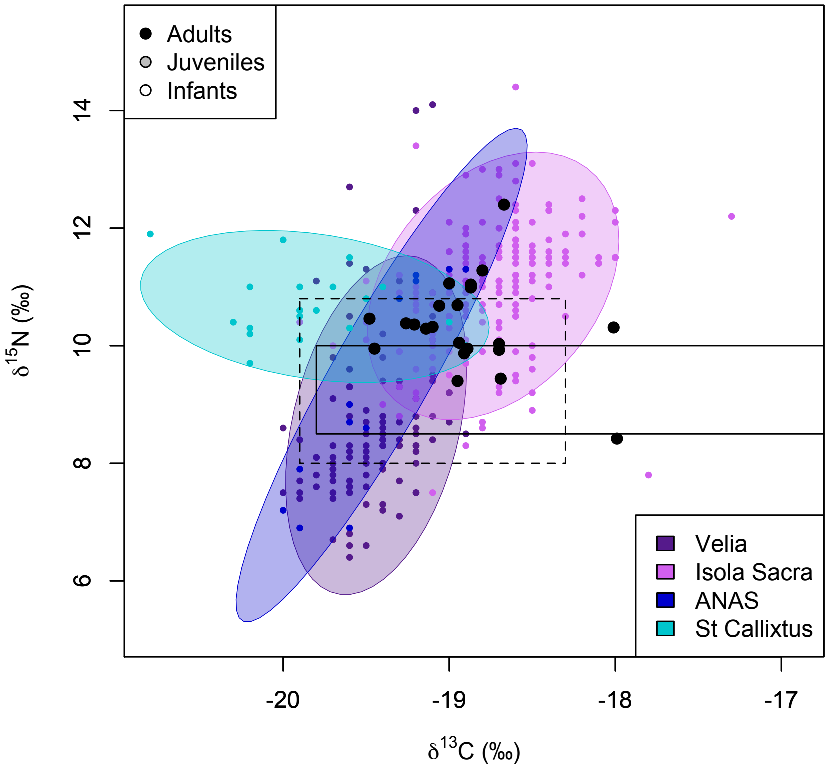

Figure 5.6: *Plot of human $\delta^{13}C$ and $\delta^{15}N$ from 1st century AD Pompeii. Previously published results from Velia (Craig et al., 2009), Isola Sacra (Prowse et al., 2004; Crowe et al., 2010), St Callixtus Catacombs, Rome (Rutgers et al., 2009) and ANAS (Prowse et al., 2004) are also shown. The 90% confidence region for each site is shown as a shaded ellipse. Also shown are the ranges of an unpublished study of other Pompeian individuals. The solid rectangle represents the 1 standard deviation range of the male isotopic ratios, and the dashed rectangle represents the 1 standard deviation range of the females (Pate, pers. comm.).*

t-test $p = 0.3076$), although one female individual had a δ^{13}C ratio as high as -16.6‰.

Pate's data can be contrasted with the Pompeian results presented in the present study, which are consistent with previous studies of coastal populations from Roman Italy, showing relatively high δ^{15}N compared to low δ^{13}C. The unpublished information I obtained about Pate's analysis shows the opposite trend, with slightly lower δ^{15}N and some individuals with extremely high δ^{13}C ratios. Instrumental methods or calibration could be the cause of these unusual isotopic ratios. Alternatively, they could reflect genuine dietary patterns that have not been identified previously. In the absence of additional information about the archaeological context of Pate's study it is impossible to speculate further. For this reason, these analyses will not be included in the meta-analysis (Chapter 6).

5.2.3 Casale del Dolce

The inland rural cemetery of Casale del Dolce included 59 adults, with a mean δ^{13}C of -20.0 ± 0.4‰ and a mean δ^{15}N of 8.0 ± 1.4‰. Individuals from Casale del Dolce have δ^{13}C and δ^{15}N ratios that are lower or similar to all other sites. Casale del Dolce has the lowest average δ^{13}C of all 16 Italian sites. This difference is significant (< 0.05) for most sites, except Palestrina, Castro dei Volsci, the Catacombs of St Callixtus and Osteria della Fontana. Casale del Dolce has similar δ^{13}C and δ^{15}N to Castro dei Volsci and Osteria della Fontana.

Table 5.4: *Summary of sex-based isotopic differences from Pompeii.*

Species	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Unknown	15	-18.96	0.25	-18.67	-19.48	10.5	0.76	12.4	9.4
Female	4	-18.86	0.58	-17.99	-19.21	9.85	0.95	10.36	8.42
Male	3	-18.58	0.53	-18.01	-19.06	10.14	0.64	10.68	9.44
Total	22	-18.89	0.37	-17.99	-19.48	10.33	0.79	12.4	8.42

All values ‰

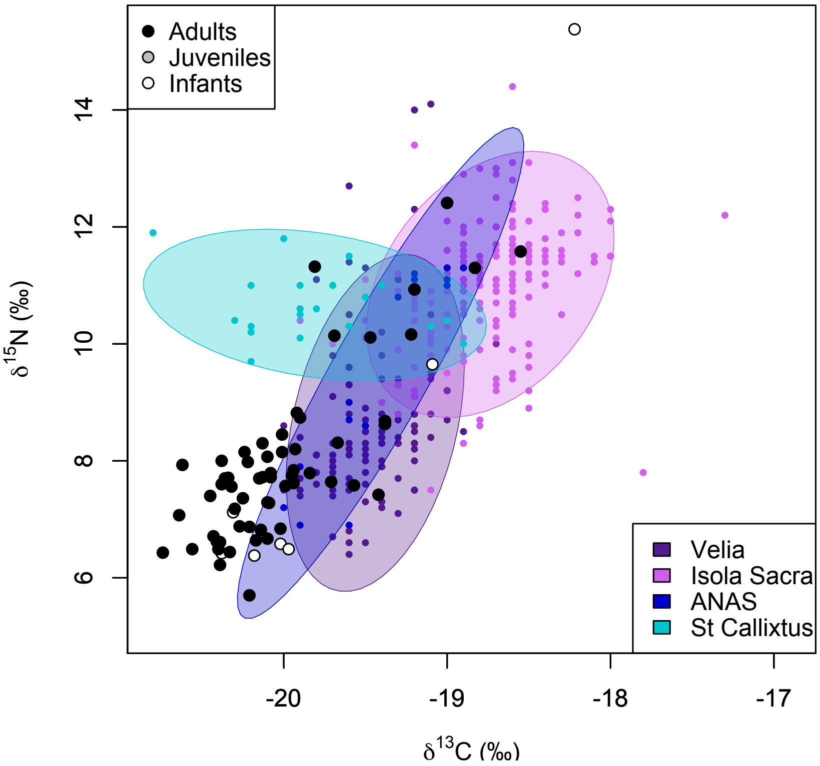

Figure 5.7: *Plot of human (adult and infant) $\delta^{13}C$ and $\delta^{15}N$ from Roman Casale del Dolce, Italy. The 90% confidence region for each site is shown as a shaded ellipse.*

See Figure 5.8 and Appendix B.1 and B.2. At Casale del Dolce the correlation between human δ^{13}C and δ^{15}N is significant (Pearson's $r = 0.79$, $p < 0.00001$).

Examination of the plot of results from Casale del Dolce suggests the data may be divided between two groups: the majority of the samples, with low δ^{15}N and low δ^{13}C, and a smaller group with comparatively high δ^{15}N and δ^{13}C (see Figure 5.7). A similar split based on δ^{15}N was noted at Roman Velia (Craig et al., 2009). A k-means cluster analysis can be used to divide the adults from Casale del Dolce into two groups (see Figure 5.9).[1] Cluster 1 contains the 49 individuals with lower isotopic ratios (mean $\delta^{13}\mathrm{C} = -20.2 \pm 0.3$‰, mean δ^{15}N

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[1] K-means cluster analysis is based on the *a priori* assumption that a certain number of clusters exist in the data (Maindonald and Braun, 2010). This test is not able to determine whether such an assumption is valid.

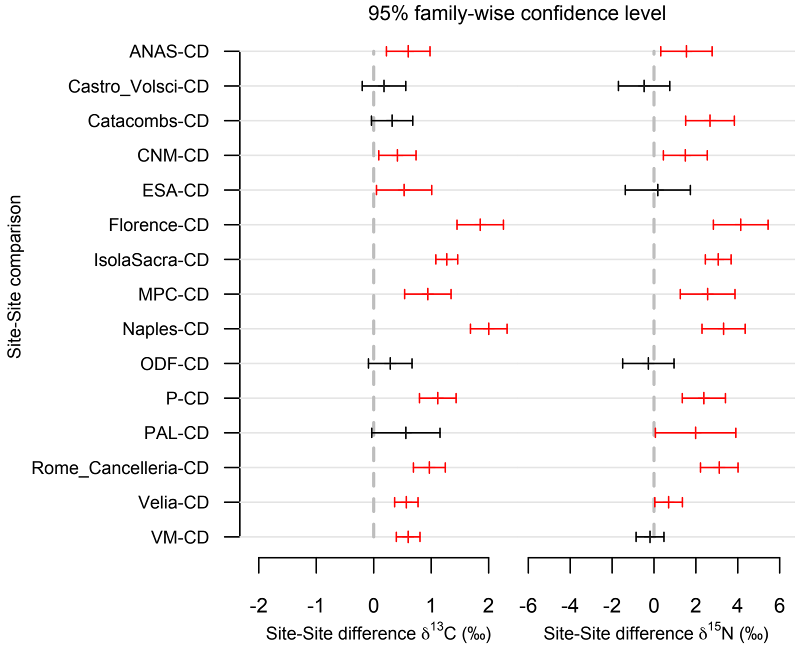

Figure 5.8: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and Casale del Dolce, based on adult individuals only. The* 95% *confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Casale del Dolce are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

$= 7.4 \pm 0.7$‰). Cluster 2 contains the remaining 10 individuals with high δ^{13}C (mean $= -19.5 \pm 0.4$‰) and high δ^{15}N (mean $= 10.5 \pm 1.2$‰).

Infants from Casale del Dolce follow similar patterns to the adults. The majority of the infants have isotopic ratios consistent with the low δ^{15}N group of adults. One individual falls into the range of the high δ^{15}N group (δ^{13}C= -19.1‰, δ^{15}N= 9.7‰). This is consistent with a fully weaned individual consuming a diet similar to the high δ^{15}N adult group, or with an individual retaining a breastfeeding signal based on a maternal baseline similar to the low δ^{15}N

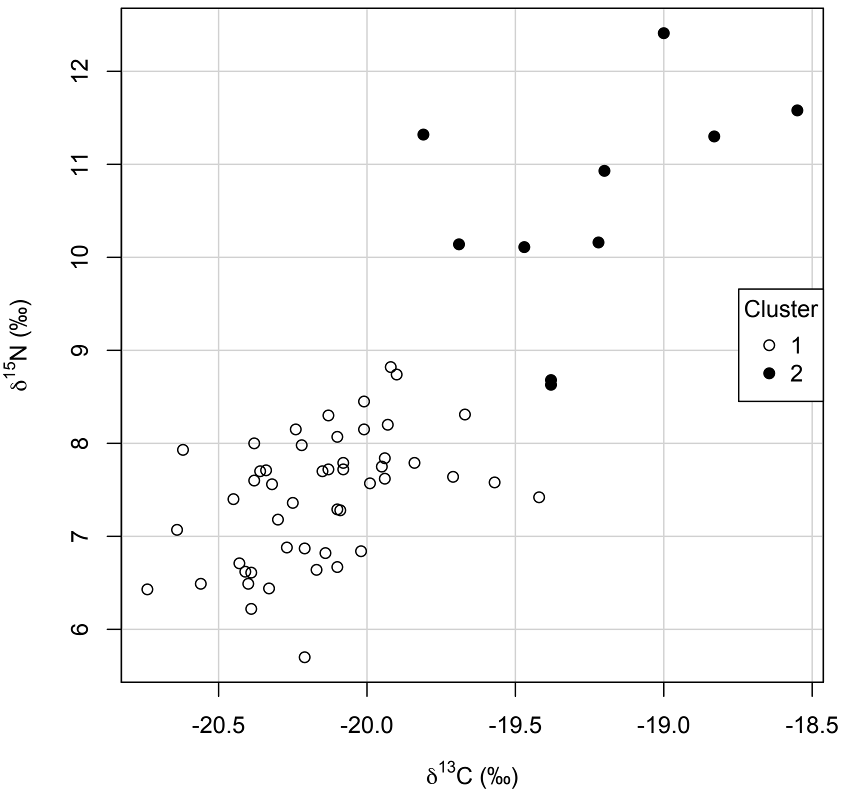

Figure 5.9: *Isotopic results of adults from Casale del Dolce divided into two clusters based on a k-means cluster analysis.*

adult group. One individual has extremely high isotopic ratios (δ^{13}C$= -18.2$‰, δ^{15}N$= 15.4$‰). This is consistent with a trophic level enrichment above a hypothetical maternal baseline in the high δ^{15}N group.

5.2.4 Osteria della Fontana

Fourteen adults were analysed from the 1st-century AD context at Osteria della Fontana, outside the city of Anagni, located near the sites of Villamagna and Casale del Dolce. The mean δ^{13}C was -19.7 ± 0.3‰ and the mean δ^{15}N was 7.7 ± 1.5‰. This average includes one individual (ODF 7) with a relatively high δ^{15}N of 11.6‰ (see Figure 5.10). There is a moderately strong positive

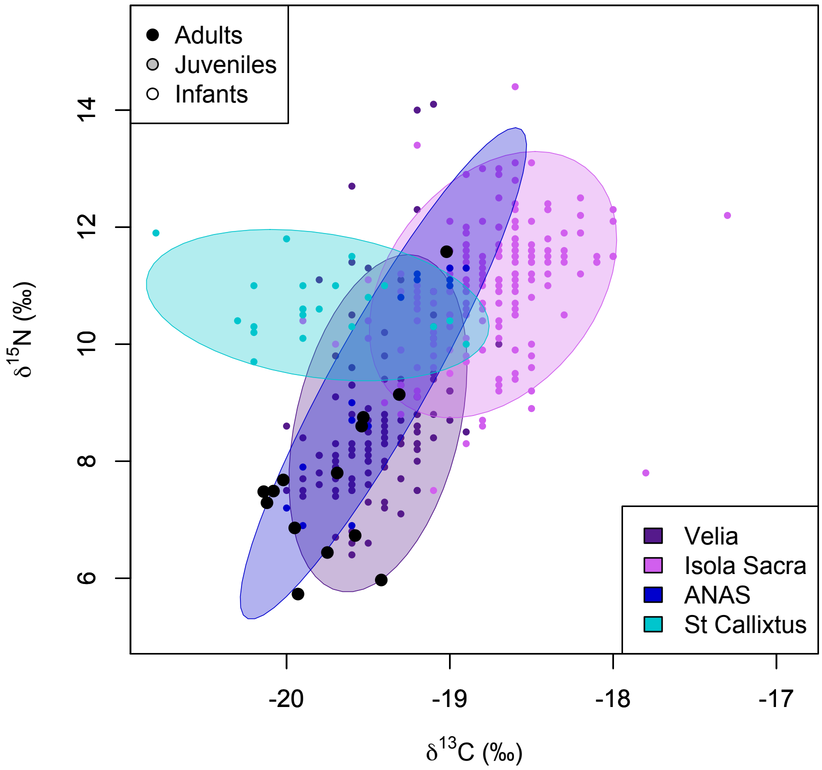

Figure 5.10: *Plot of human $\delta^{13}C$ and $\delta^{15}N$ from Roman Osteria della Fontana, Italy. The 90% confidence region for each site is shown as a shaded ellipse.*

correlation between δ^{13}C and δ^{15}N at Osteria della Fontana (Pearson's $r = 0.60$, $p = 0.02$). The isotopic results from Osteria della Fontana are most similar to those of other inland Italian sites. Based on both δ^{13}C and δ^{15}N, Osteria della Fontana is indistinguishable from Castreo dei Volsci ($p = 1.0$ and 1.0), Casale del Dolce ($p = 0.39$ and 1.0), Esanatoglia($p = 0.98$ and 1.0), and Villamagna ($p = 0.18$ and 1.0). It is also indistinguishable from Velia, a coastal site ($p = 0.35$ and 0.24). See Figure 5.11 and Appendix B.1 and B.2. For all other sites, which are primarily coastal sites, the differences in both δ^{13}C and δ^{15}N are significant ($p < 0.05$, see **??**). The relationship between coastal and inland sites will be explored more generally in 5.5 below.

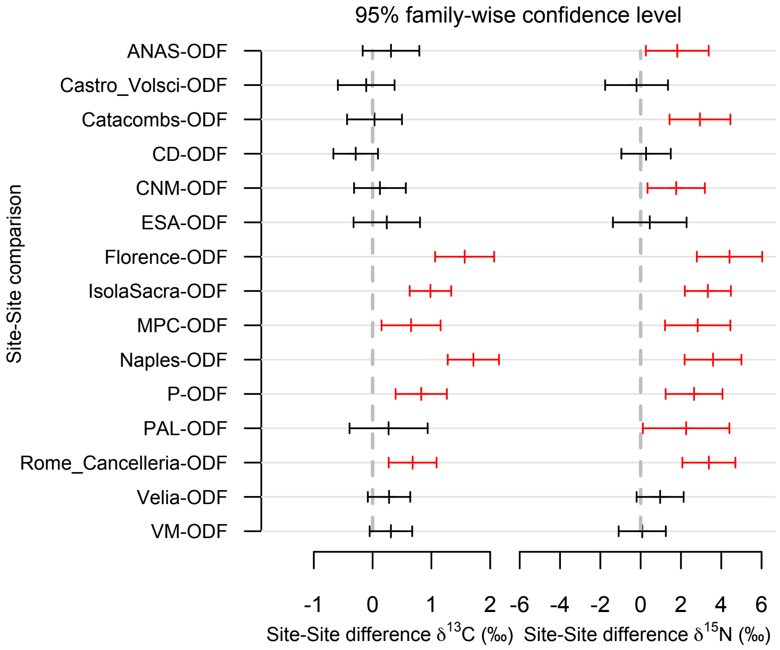

Figure 5.11: *Comparison of δ^{13}C and δ^{15}N between Italian sites and Osteria della Fontana, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Osteria della Fontana are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

5.2.5 Civitanova Marche

Twenty-one adults were analysed from the coastal Roman site of Civitanova Marche (CNM). The average δ^{13}C is $-19.6 \pm 0.6‰$ and the average δ^{15}N is $9.5 \pm 1.3‰$. However, these averages misrepresent a large spread in data with several outliers (see Figure 5.12). The majority of the samples (n = 15) have relatively terrestrial δ^{13}C (mean = $-19.9 \pm 0.2‰$) and relatively high δ^{15}N (mean = $9.0 \pm 0.4‰$). There are also four individuals who have higher δ^{13}C

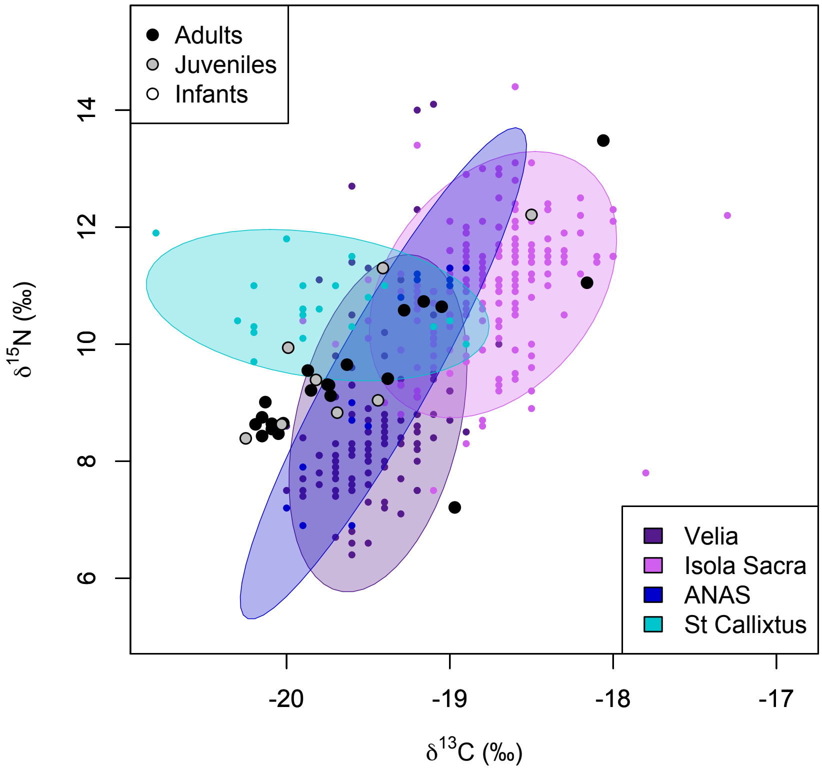

Figure 5.12: *Plot of human (adult and juvenile) $\delta^{13}C$ and $\delta^{15}N$ from Roman Civitanova Marche, Italy. The 90% confidence region for each site is shown as a shaded ellipse.*

and higher δ^{15}N, which is comparable with results from Palestrina, and with the high δ^{15}N group from Casale del Dolce. There are two outliers: one individual (CNM 19) has a significantly lower δ^{15}N ratio (7.2‰). One individual (CNM 4) has high δ^{13}C (−18.1‰) and δ^{15}N (13.5‰) which is comparable with the highest values obtained from Isola Sacra.

When results from CNM are considered as a single group, δ^{13}C ratios are lower than most other Roman Italian sites. CNM has significantly lower δ^{13}C compared to Marcellino e Pietro ($p = 0.008$), Pompeii ($p < 0.001$), Palazzo della Cancelleria (Rome) ($p < 0.001$), Naples ($p < 0.001$), Florence ($p < 0.001$) and Isola Sacra ($p < 0.001$). On average δ^{13}C at CNM is significantly higher

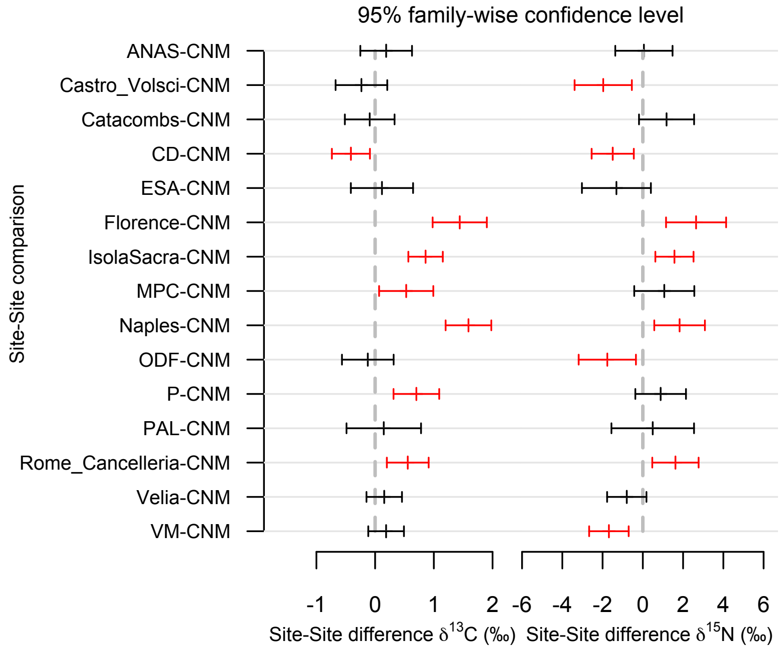

Figure 5.13: *Comparison of δ^{13}C and δ^{15}N between Italian sites and Civitanova Marche, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Civitanova Marche are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

than Casale del Dolce (p = 0.001). CNM has intermediate δ^{15}N values for Italy. At CNM δ^{15}N is significantly higher than ODF, Villamagna, Casale del Dolce, and Castro dei Volsci ($p < 0.05$ for all). It is significantly lower in δ^{15}N compared to Palazzo della Cancelleria (Rome), Naples, Florence, and Isola Sacra ($p < 0.05$ for all). Based on both δ^{13}C and δ^{15}N, CNM is indistinguishable from ANAS, the Catacombs of St Callixtus, Esanatoglia, Marcellino Palestrina, and Velia. For details see Figure 5.13 and Appendix B.1 and B.2. The adult δ^{13}C and δ^{15}N ratios from Civitanova Marche also show a significant positive

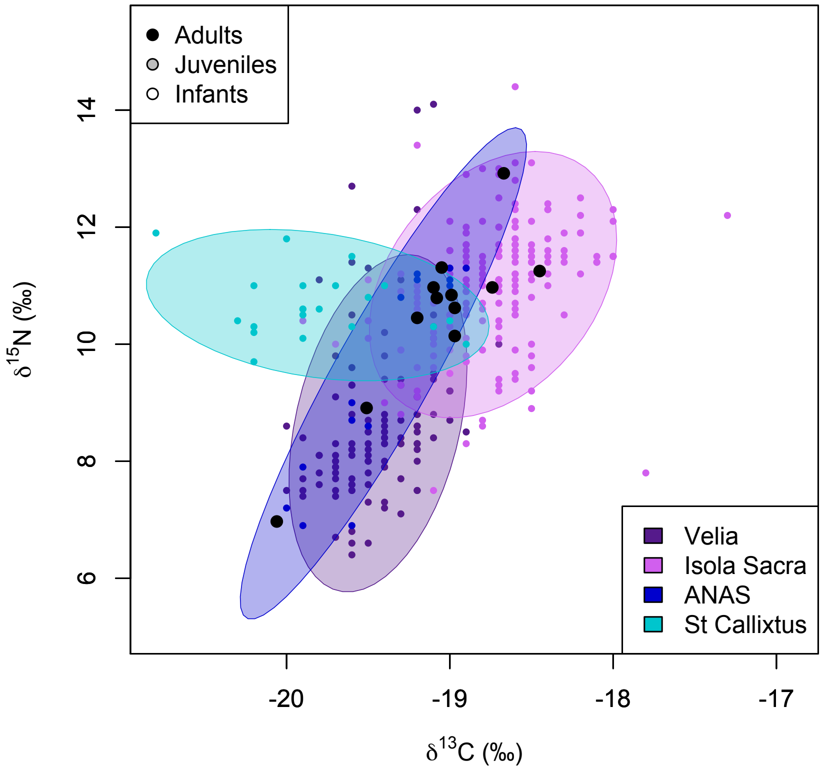

Figure 5.14: *Plot of human (adult and juvenile) δ^{13}C and δ^{15}N from the catacombs of SS Marcellino e Pietro, Rome. The* 90% *confidence region for each site is shown as a shaded ellipse.*

correlation (Pearson's $r = 0.74$, $p = 0.0001$).

5.2.6 The Catacombs of SS Marcellino e Pietro, Rome

Twelve individuals were sampled from the mid 3rd to early 5th-century Christian catacombs of SS Marcellino e Pietro, Rome. These were all cranial fragments to ensure that unique individuals were sampled. Mean values were -19.1 ± 0.4‰ for δ^{13}C and 10.5 ± 1.4‰ for δ^{15}N. One individual had extremely low isotopic ratios ($\delta^{13}\text{C} = -20.1$‰, $\delta^{15}\text{N} = 7.0$‰). At Marcellino e Pietro δ^{13}C and δ^{15}N ratios are significantly correlated, (Pearson's $r = 0.89$, $p = 0.0001$).

From Figure 5.14 it is clear that the individuals from Marcellino e Pietro differ from the early Christian population from St Callixtus, but are similar to other Roman sites. The group from Marcellino e Pietro has significantly higher δ^{13}C ($p = 0.001$) compared to St Callixtus, while δ^{15}N is similar ($p = 1.0$). For details see Figure 5.15 and Appendix B.1 and B.2.

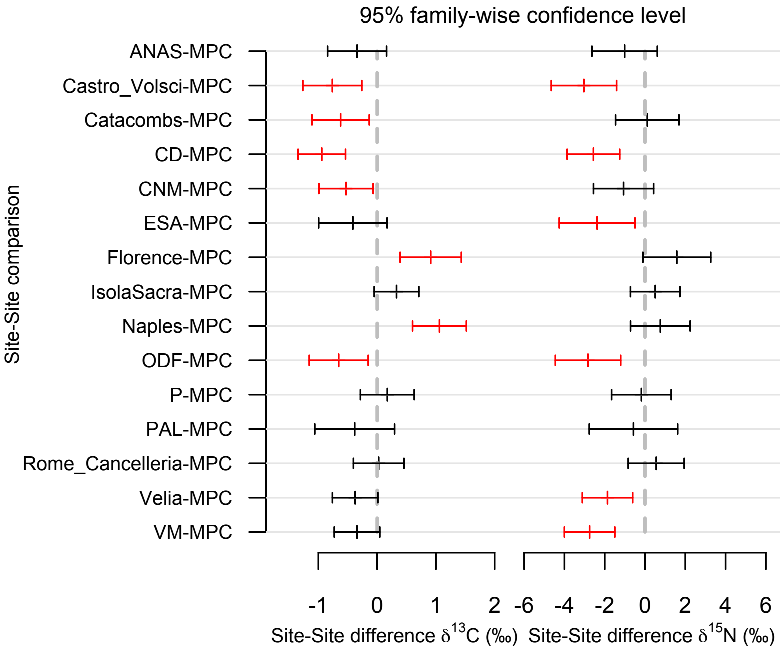

Figure 5.15: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and the catacombs of SS Marcellino e Pietro, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from the catacombs of SS Marcellino e Pietro are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

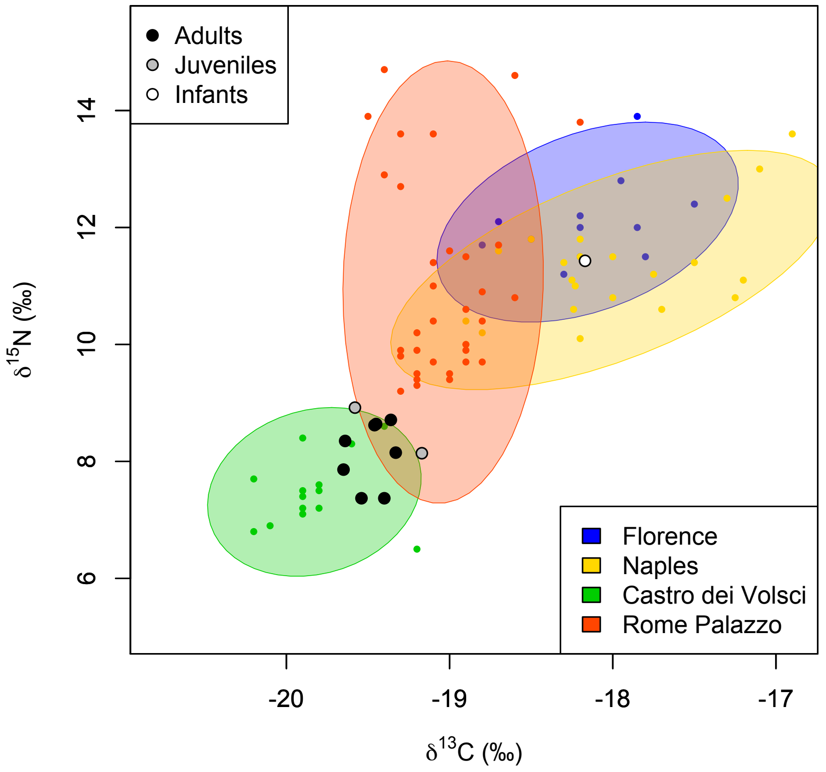

Figure 5.16: *Plot of human $\delta^{13}C$ and $\delta^{15}N$ from Esanatoglia. Shaded area represents the 90% confidence ellipse for previously published sites: Rome Palazzo della Cancelleria (Salamon et al., 2008), Naples and Florence (Fornaciari, 2008).*

5.3 Early Medieval sites from Lazio

5.3.1 Esanatoglia

Eight adult individuals were analysed from Esanatoglia, with an average δ^{13}C of -19.5 ± 0.1‰ and δ^{15}N of 8.1 ± 0.6‰ (see Figure 5.16). All the individuals from this site cluster closely together and there are no obvious outliers. There were no significant correlations between δ^{13}C and δ^{15}N at Esanatoglia. Esanatoglia's intermediate isotopic ratios mean that it is similar to many sites. It has significantly lower δ^{13}C and δ^{15}N compared to Pompeii, Naples, Florence, and Isola Sacra ($p < 0.05$). It is significantly higher in δ^{13}C compared to Casale del Dolce ($p = 0.02$). It is significantly lower in δ^{15}N compared to the Catacombs of St Callixtus, Marcellino e Pietro, and Palazzo della Cancelleria (Rome). As mentioned above, Esanatoglia is indistinguishable from Osteria della Fontana, Palestrina and Civitanova Marche, and is also similar to ANAS, Castro dei Volsci Velia and Villamagna. For details see Figure 5.17 and Appendix B.1 and B.2.

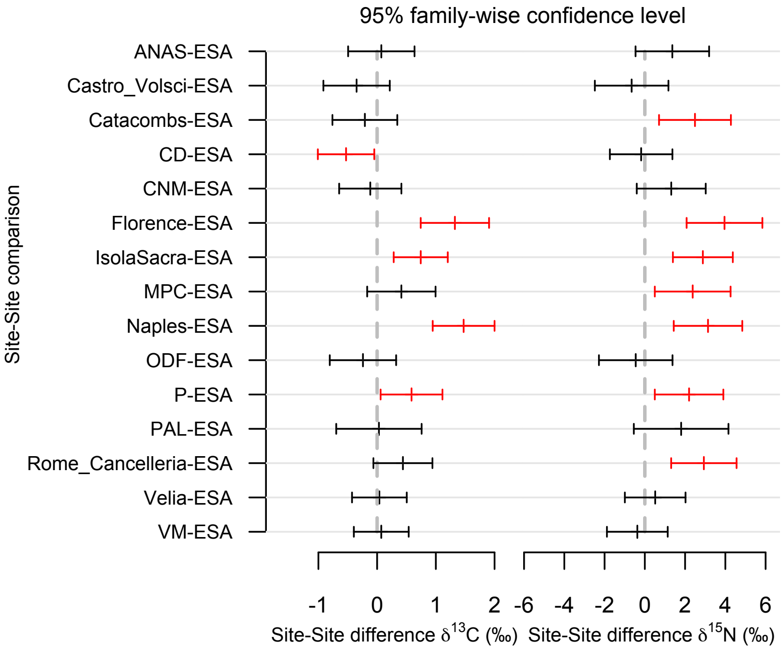

Figure 5.17: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and Esanatoglia, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Esanatoglia are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

5.4 Results from Medieval Villamagna

Results from Villamagna from all periods (AD 700 to 1500) of the site are reported together. This includes intra-site comparisons based on age, location, period, and sex.

5.4.1 Age-based differences at Villamagna

Age estimates for individuals at Villamagna were recorded as ranges, from which a midpoint was estimated. The midpoint estimate was used to divide individuals into 9 age categories. For some individuals, only approximate ages ('Adult', 'Juvenile' or 'Infant') were available. Those individuals with ages described as ranges and midpoints were also divided into the same three categories as follows: infants were individuals with midpoint age estimates less than or equal to two years, juvenils were individuals with midpoint age estimates between two and sixteen years, and adults were individuals with midpoint age estimates greater than or equal to sixteen years. As expected, there are significant isotopic differences between different age categories. Breastfeeding infants will exhibit higher δ^{15}N and slightly higher δ^{13}C due to a trophic level effect (see Chapter 3). It is also notable that juveniles have lower δ^{13}C and δ^{15}N compared to both adults and infants. These differences are summarized in Table 5.5. Differences in both δ^{13}C and δ^{15}N are significant between Adults and Juveniles (Tukey post-hoc comparison for δ^{13}C: difference $= -0.17, 95\%$CI [-0.004, -0.33], $p = 0.04$; for δ^{15}N: difference $= -0.55, 95\%$CI [-0.07, -1.04], $p = 0.02$), Adults and Infants (Tukey post-hoc comparison for δ^{13}C: difference $= 0.40, 95\%$CI [0.22, 0.59], $p < 0.0001$; for δ^{15}N: difference $= 1.7, 95\%$CI [1.2, 2.3], $p < 0.0001$), and Infants and Juveniles (Tukey post-hoc comparison for δ^{13}C: difference $= -0.57, 95\%$CI [-0.78, -0.37], $p < 0.0001$; for δ^{15}N: difference $= -2.28, 95\%$CI [-2.89, -1.67], $p < 0.0001$).

A more detailed breakdown of age-related differences can be obtained by observing the 9 more closely definted categories. Pairwise comparisons of δ^{13}C

Table 5.5: *Summary of isotopic results for different age categories from the Monastery and Church at Villamagna. This excludes the four Late Antique individuals from a separate part of the site.*

Age	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Adult	113	-19.4	0.4	-17.7	-20.2	7.8	1.1	12.9	5.3
Juvenile	49	-19.6	0.4	-18.7	-20.0	7.2	1.0	9.8	5.2
Infant	39	-19.0	0.4	-18.1	-20.0	9.5	1.2	12.6	6.9
Unknown	1	-19.2	–	–	–	7.2	–	–	–

All values ‰

Table 5.6: *Summary of isotopic results for subdivided age categories at Villamagna. Unknown ages are not more precisely known, but include 19 Adults, 2 Juveniles, 1 infant and 1 unaged individual.*

Age	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
0-1 yr	19	-18.92	0.34	-18.34	-19.93	9.8	0.96	12.58	8.63
1-2 yr	24	-19.2	0.37	-18.18	-19.96	8.87	1.21	11.09	6.88
3-5 yr	11	-19.67	0.18	-19.21	-19.85	7.42	0.9	8.98	6.07
6-11 yr	20	-19.55	0.37	-18.7	-20.01	6.96	0.92	9.79	5.42
12-15 yr	11	-19.68	0.21	-19.35	-19.96	6.81	0.81	7.9	5.16
16-19 yr	8	-19.41	0.72	-18.09	-19.94	7.79	1.5	10.04	6.01
20-29 yr	23	-19.49	0.29	-18.55	-19.96	7.53	0.8	9	5.93
30-39 yr	34	-19.36	0.47	-17.73	-20.04	7.98	1.11	11.02	6.56
40-49 yr	28	-19.43	0.22	-18.96	-19.91	7.63	0.8	9.54	5.96
50+ yr	1	-19.86	NA	-19.86	-19.86	7.55	NA	7.55	7.55
Unknown	23	- 19.3	0.4	-18.1	-20.2	8.0	1.7	12.9	5.3

All values ‰

and δ^{15}N between different age categories were calculated with an analysis of variance test, applying a Tukey Honestly Significant Difference post-hoc correction at the 95% confididence limit. For details see Table 5.7 and 5.8. Note that there was only one individual with a midpoint age estimate greater than 50 years (see Table 5.6). Therefore there were no significant differences between this individual and other age categories and it will be omitted from the discussion of age-related variation.

Individuals with midpoint age estimates of less than 1 year have the highest δ^{15}N, 0.9‰to 3‰ higher than other age categories on average. The difference in δ^{15}N between this age category and others is significant ($p < 0.001$) except for indivuals with midpoint age estimates of 1–2 years. Individuals with midpoint age estimates less than 1 year also have significantly higher δ^{13}C ratios compared to most other age categories. Individuals aged 1–2 years have also significantly higher δ^{15}N compared to most other age categories (see Table 5.8) and higher δ^{13}C ratios compared to individuals in the 3–5 year and 12–15 year categories. Individuals with midpoint age estimates between 3 and 5 years are intermediate in δ^{13}C and δ^{15}N, with no significant differences. The two categories of 6–11 years and 12–15 years have the lowest average δ^{15}N and δ^{13}C estimates, but on a pairwise comparison basis, the only significant difference is in the δ^{15}N ratios which are 1.0 and 1.2‰ lower than individuals in the 30 to 39 midpoint age estimat category. There are no other significant pairwise differences. Adult δ^{13}C and δ^{15}N ratios are moderately correlated, (Pearson's $r = 0.54$, $p < 0.0001$). See also Figure 5.18.

Table 5.7: *Table showing the significance of pairwise comparisons of $\delta^{13}C$ differences between different age categories at Villamagna. Significance codes ($p < 0.001$ =***, $p < 0.01$ = **, $p < 0.05$ =*) based on Tukey's Honestly Significant Difference family-wise comparison for the* 95% *confidence interval.*

Age-Age	0-1yr	1-2yr	3-5yr	6-11yr	12-15yr	16-19yr	20-29yr	30-39yr	40-49yr
1-2yr	-0.28	–	–	–	–	–	–	–	–
3-5yr	-0.74 ***	-0.46 *	–	–	–	–	–	–	–
6-11yr	-0.63 ***	-0.35	0.12	–	–	–	–	–	–
12-15yr	-0.76 ***	-0.48 *	-0.02	-0.13	–	–	–	–	–
16-19yr	-0.48	-0.2	0.26	0.14	0.28	–	–	–	–
20-29yr	-0.57 ***	-0.29	0.17	0.05	0.19	-0.09	–	–	–
30-39yr	-0.44 **	-0.16	0.3	0.18	0.32	0.04	0.13	–	–
40-49yr	-0.51 ***	-0.23	0.24	0.12	0.25	-0.02	0.07	-0.06	–
50+yr	-0.93	-0.65	-0.19	-0.31	-0.17	-0.45	-0.36	-0.49	-0.43

The differences reported here between infant and adult isotopic ratios are similar to those reported for infants from the 18th and 19th century population

Table 5.8: *Table showing the significance of pairwise comparisons of $\delta^{15}N$ differences between different age categories at Villamagna. Significance codes ($p < 0.001$ =***, $p < 0.01$ = **, $p < 0.05$ =*) based on Tukey's Honestly Significant Difference family-wise comparison for the* 95% *confidence interval.*

Age-Age	0-1yr	1-2yr	3-5yr	6-11yr	12-15yr	16-19yr	20-29yr	30-39yr	40-49yr
1 to 2yr	-0.92	–	–	–	–	–	–	–	–
3 to 5yr	-2.38 ***	-1.45 **	–	–	–	–	–	–	–
6 to 11yr	-2.83 ***	-1.91 ***	-0.46	–	–	–	–	–	–
12 to 15yr	-2.98 ***	-2.06 ***	-0.61	-0.15	–	–	–	–	–
16 to 19yr	-2 ***	-1.08	0.37	0.83	0.98	–	–	–	–
20 to 29yr	-2.26 ***	-1.34 ***	0.11	0.57	0.72	-0.26	–	–	–
30 to 39yr	-1.81 ***	-0.89 *	0.56	1.02 *	1.17 *	0.19	0.45	–	–
40 to 49yr	-2.16 ***	-1.24 ***	0.21	0.67	0.82	-0.16	0.1	-0.35	–
50+yr	-2.25	-1.32	0.13	0.59	0.74	-0.24	0.02	-0.43	-0.08

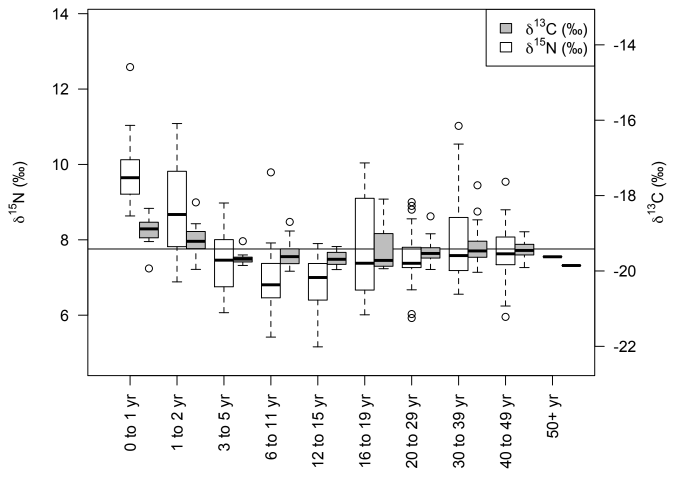

Figure 5.18: *Box plot of isotopic results ($\delta^{13}C$ and $\delta^{15}N$) by age category at Villamagna. $\delta^{13}C$ and $\delta^{15}N$ are plotted on the same graph, relative to the overall adult mean mean for each (shown as a solid line).*

from Christ Church, Spitalfields (Nitsch et al., 2011), where infants under the age of 3 were 0.36‰ higher on average in δ^{13}C and 1.23‰ higher in δ^{15}N. The slightly higher average difference between infants and adults at Villamagna may relate to breastfeeding being more extensively and intensively practised, but could also be explained by differences in the precise age distribution between the two groups. The elevation in δ^{15}N due to breastfeeding is highly age-dependent, with a peak in δ^{15}N between 6 and 18 months (Nitsch et al., 2011). Since the ages of the Villamagna individuals are imprecisely known, they cannot be uncritically compared to the individuals from Spitalfields, where historical records provided precise ages for many individuals.

5.4.2 Chronological and spatial differences in isotopic ratios at Villamagna

For Villamagna, a multivariate linear regression was used to determine the effect of Phase (Early Medieval, Central Medieval or Late Medieval), Sex, Location and Grave type (simple earth, built tomb or other) on δ^{13}C and δ^{15}N based on adult individuals only. For both δ^{13}C and δ^{15}N an initial complex model, which included all the above mentioned factors, was compared to a simplified model, including only those factors which significantly affected the output. Since in both cases the simplified model was not significantly different from the complex model (ANOVA for δ^{13}C: $F(1,\ 108) = 1.62$, $p = 0.12$; for δ^{15}N: $F(1,\ 108) = 0.58$, $p = 0.81$) the simpler model was adopted as the more parsimonious explanation of the results. The summary statistics for the complex and simplified models are displayed in Appendix B.2).

It should be noted that these models are not able to explain the majority of the variation observed at Villamagna. For the simplified δ^{13}C model, individuals from the Late Medieval phase (including indivdiduals of unidentified phase) were compared to the group of both Central and Early Medieval phases. Sex categories were simplified, such that uncertain males (‘M?’) were categorised as male, and uncertain females (‘F?’) were categorised as female. Adults of

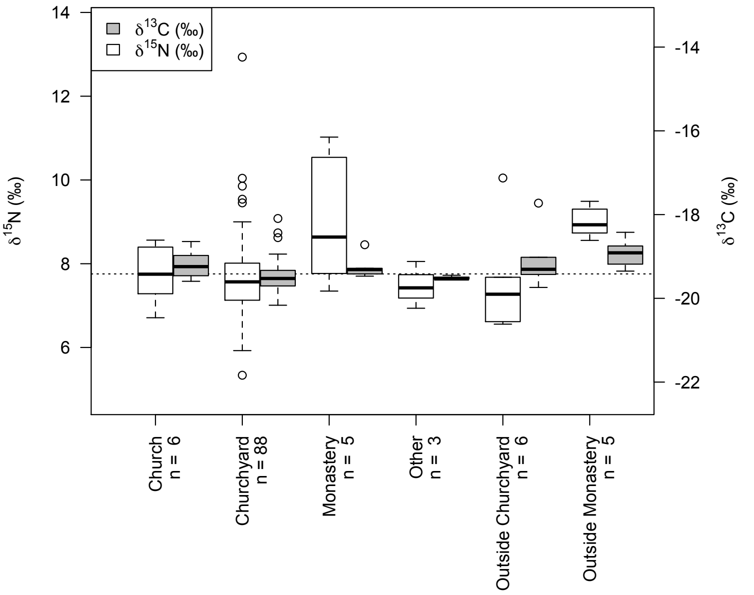

Figure 5.19: *Box plot of $\delta^{13}C$ and $\delta^{15}N$ of adults from Villamagna for different locations.*

unknown sex were also included. The six individuals from the area outside the churchyard were compared to the rest of the individuals, since this was the only location that produced a significantly different average δ^{13}C ratio. None of the other factors recorded about the burials at Villamagna provided a significant explanation for the variation in δ^{13}C ratios. As as result, the adjusted R squared of the simple δ^{13}C multivariate regression was 0.24, $F(4, 108) = 9.966$, $p =< 0.0001$). The simplified δ^{15}N multivariate regression employed identical parameters, except that the group buried in the monastery and outside the monastery were compared (as a single group) to a single group consisting of all others. None of the other factors that were known about the indviduals proved significant for δ^{15}N, meaning that a large portion of the variation was unexplained: adjusted R squared = 0.1492, $F(4, 108) = 5.912$, $p = 0.0002$.

The six individuals buried outside the churchyard had significantly higher δ^{13}C (0.5‰) compared to the others ($p = 0.001$). However, inspection of Figure 5.19 suggests this is due to a single outlier. The five adults buried in association with the monastery, together with the five individuals buried

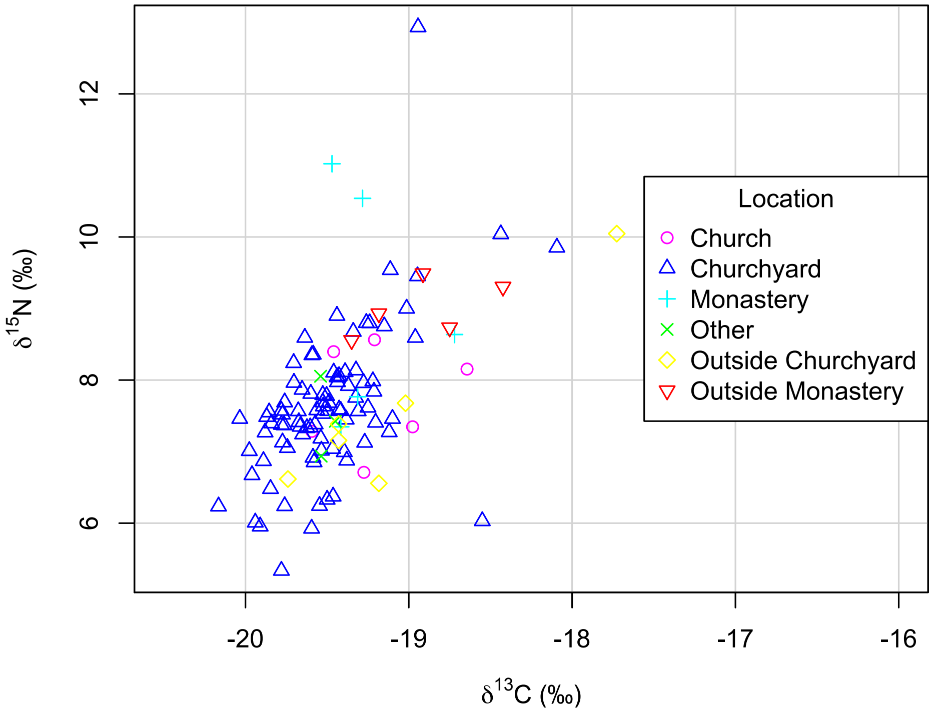

Figure 5.20: *Plot of $\delta^{13}C$ and $\delta^{15}N$ by site location code for all adults from Villamagna.*

outide the monastery had significantly higher (1.8‰) δ^{15}N compared to others ($p < 0.0001$). As noted in Chapter 4, the group buried outside the monastery were predominantly buried on a N-S axis, distinctive compared to the W-E burials of almost all other individuals at the site. The isotopic evidence provides a further indication of this group was distinctive. On the other hand, although the individuals buried in the Church were thought to represent an elite subgroup, there was no evidence for isotopic differences between this group and other locations. See Figure 5.20.

Table 5.9 provides a summary of the isotopic results according to phase. Figure 5.21 shows a box plot for adults δ^{13}C and δ^{15}N by period. The multivariate regression shows that there are small but significant differences due to phase. The Late Medieval phase (including the three individuals of unknown phase) has slightly lower δ^{13}C (estimated effect of -0.33‰, $p = 0.0002$) compared to the Early Medieval and Central Medieval (combined) phases. The slightly

Table 5.9: *Summary of isotopic results for different phases at Villamagna*

Phase	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
Early Medieval AD 700-950	3	-19.47	0.29	-19.2	-19.77	7.38	0.23	7.59	7.13
Central Medieval AD 950-1250	16	-19.08	0.45	-18.09	-19.58	8.15	1.45	11.02	6.03
Late Medieval AD 1250-1500	91	-19.47	0.35	-17.73	-20.17	7.71	1.05	12.93	5.34
Unknown	3	-19.51	0.05	-19.45	-19.54	7.47	0.56	8.05	6.94

All values ‰

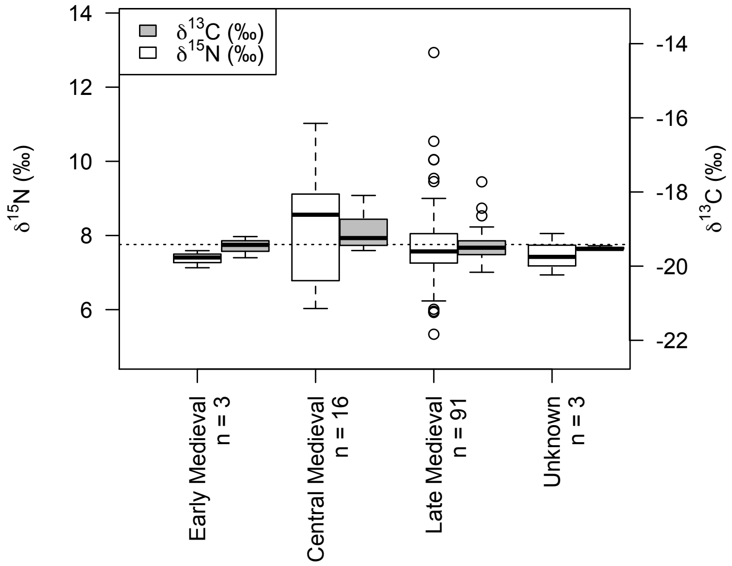

Figure 5.21: *Box plot of $\delta^{13}C$ and $\delta^{15}N$ for different phases at Villamagna, adults only.*

higher δ^{15}N ratio (0.5‰) between adults from the Early and Central medieval phases compared to the Late Medieval phases is not significant ($p = 0.1$), and is largely due to the difference for the 16 individuals from the Central Medieval phase. See Figure 5.22. This mostly reflects the differences in isotopic ratio for the five adults buried as part of the unusual group outside the monastery, with N-S orientation and the high δ^{15}N ratios already noted.

For adults, sex is divided into five categories, Unknown, Female, Female?, Male and Male?. Figure 5.24 and Table 5.10 show that females have slightly

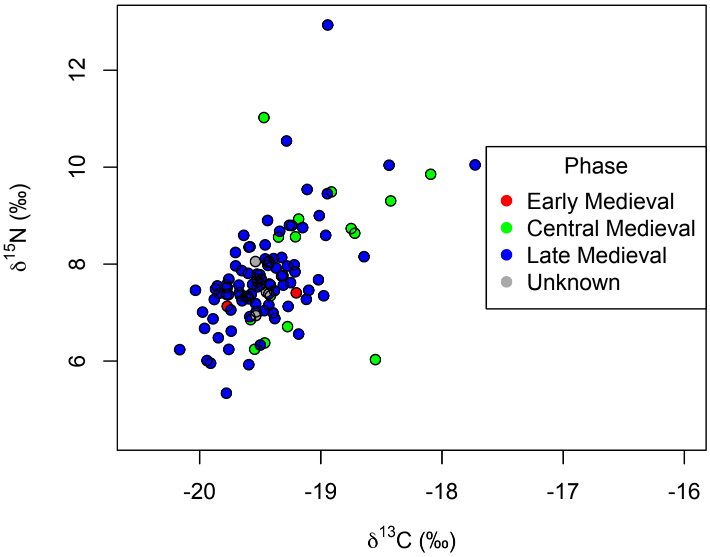

Figure 5.22: *Plot of δ^{13}C and δ^{15}N for adults from Villamagna, coloured by phase*

lower δ^{15}N compared to males, but that the questionable females tend to be slightly higher. Combining all sexes into three categories (M, F, U) in the multiviariate regression, the difference between M and F for δ^{13}C is significant (estimated effect is 0.24‰,$p = 0.002$). The difference in δ^{15}N is not very significant (estimated effect is 0.38‰, $p = 0.1$). However, of the 11 adults at Villamagna with δ^{15}N greater than 9‰, there are six males, three probable males, one probable female and three unknowns (see Figure 5.23).

Table 5.10: *Summary of adult isotopic results for by sex at Villamagna*

Phase	N	δ^{13}C	1σ	Max	Min	δ^{15}N	1σ	Max	Min
F	27	-19.67	0.23	-19.02	-20.17	7.25	0.59	8.8	5.93
F?	4	-19.29	0.59	-18.42	-19.71	8.45	0.86	9.3	7.34
All female	31	-19.62	0.31	-18.42	-20.17	7.4	0.73	9.3	5.93
M	53	-19.35	0.33	-18.09	-19.91	7.88	1.01	11.02	5.96
M?	5	-19.44	0.43	-18.91	-19.89	7.79	1.22	9.49	6.56
All male	58	-19.36	0.34	-18.09	-19.91	7.87	1.01	11.02	5.96
Unknown	24	-19.29	0.48	-17.73	-19.94	7.93	1.53	12.93	5.34

All values ‰

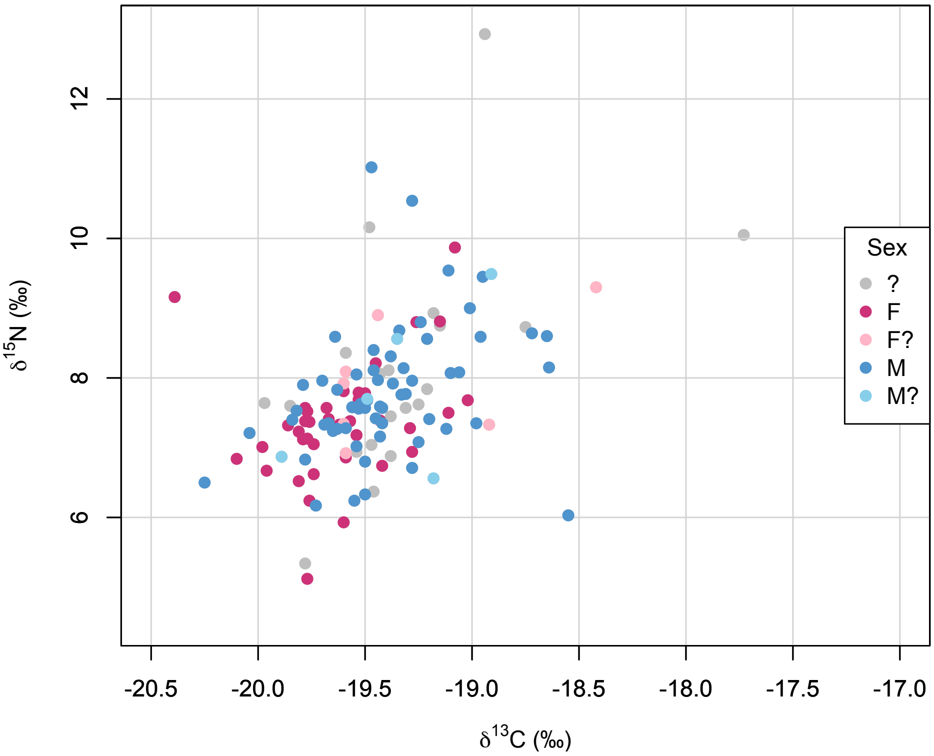

Figure 5.23: *Plot of $\delta^{13}C$ and $\delta^{15}N$ of adults from Villamagna by sex.*

Grave types were recorded as either built tombs, simple earth grave or other/unknown. It was hypothesized that individuals from more elaborate built tombs were of higher status, but Figure 5.25 shows that the type of graves do not correspond to any significant isotopic differences overall.

5.4.3 Individuals with unusual isotopic ratios from Villamagna

The results above indicated several individuals with unusual isotopic ratios, and it is worth discussing their archaeological context in more detail. Two young adults (aged 15-20 years) were noted with unusually high δ^{15}N. VM2080 (δ^{13}C $= -18.4$‰, δ^{15}N $= 10.0$‰) was one of four individuals buried in a marble-slab tomb. Individuals from this tomb do not have unusual isotopic ratios compared to the other burials from this site. The other four individuals exhibit a range of isotopic values (δ^{13}C from -19.7 to -19.0‰, δ^{15}N from 6.9

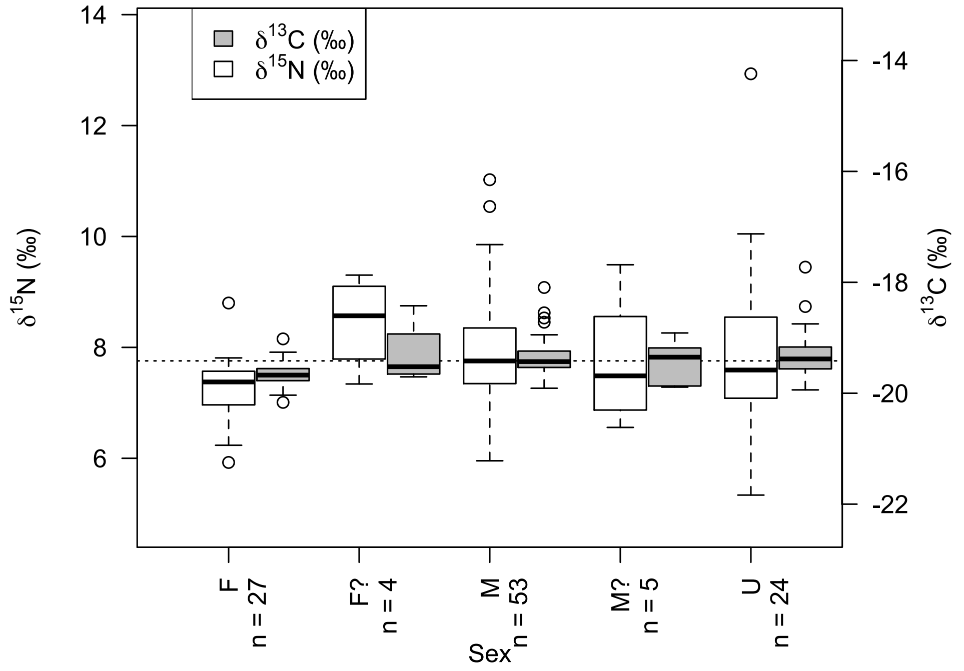

Figure 5.24: *Box plot of* $\delta^{13}C$ *and* $\delta^{15}N$ *for adults from Villamagna by sex.*

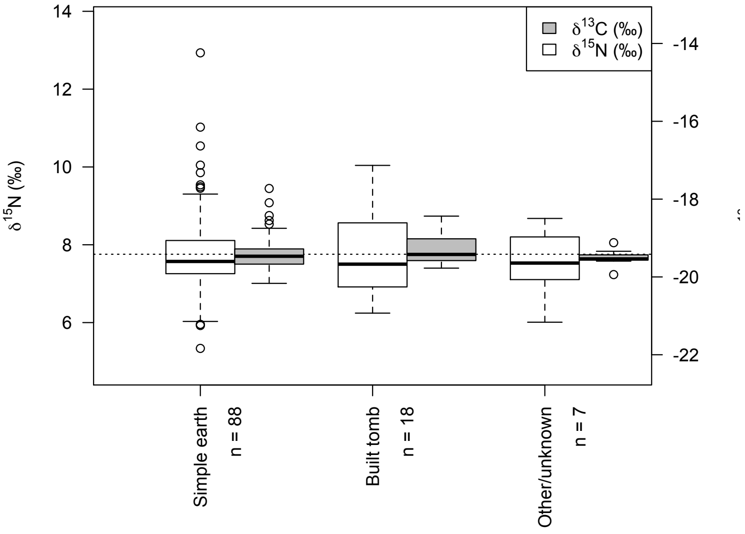

Figure 5.25: *Plot of* $\delta^{13}C$ *and* $\delta^{15}N$ *for all adults from Villamagna by grave type*

to 8.6 ‰) comparable with the site averages. VM4274 (δ^{13}C = −18.1, δ^{15}N = 9.9) is one of the individuals from the Central medieval period, buried within the churchyard. This male individual's burial was disturbed by cutting for later building at the site.

As noted above, the five adults from the area outside of the Monastery, buried on an unusual N-S axis, have especially high δ^{15}N. This unusual group also includes two juveniles, making a total of seven. However, one of the juveniles (VM4101) has unusually low δ^{15}N at 5.2‰. This individual's isotopic ratios are well within the faunal ratios from this site, and are therefore consistent with a similar, largely herbivorous diet.[2] The other juvenile from this group (VM4193) is notable for relatively high δ^{13}C (−18.7‰) and average δ^{15}N (7.1‰). Other individuals also had notably high δ^{13}C although the differences between adults were not signficant overall, such as VM4193 (δ^{13}C = −18.7) and VM4118 (δ^{13}C = −18.4‰). There is no other archaeological information to suggest why these individuals may have had different burial practices or dietary habits.

There is a large range in δ^{15}N among adults at Villamagna. There are five adults with δ^{15}N greater than or equal to 10‰: VM2080(10.0‰), VM2809 (12.9‰), VM4067 (10.0‰), VM4084 (10.5‰), and VM4348 (11.0‰). VM4348 and VM4084 were both male, while sex was unknown for the other three. All except 2080 were buried on a N-S orientation, but were buried in a variety of locations. They were not part of the separate group of N-S burials noted above.[3] There are three adults and three juveniles with δ^{15}N values 6‰ or lower: VM4374 (adult male, δ^{15}N 6.0‰), VM2969 (adult, unknown sex, 5.3‰), VM4246 (adult female, 5.9‰), VM2460 ($9-10$ year old juvenile, 5.4‰), VM4101 ($9-10$ year old juvenile, 5.4‰, part of the unusual N-S central

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[2] The unusually low δ^{15}N ratio calls into question whether the bone sampled was truly human and not animal. Given that bones were sampled within days of the initial excavation, if not taken from ribs in situ, it is extremely unlikely that this unual result is due to confusion between human and animal bone.

[3] Due to incomplete orientation records for the excavation at the time of writing, it is not possible to investigate isotopic differences based on orientation more systematically.

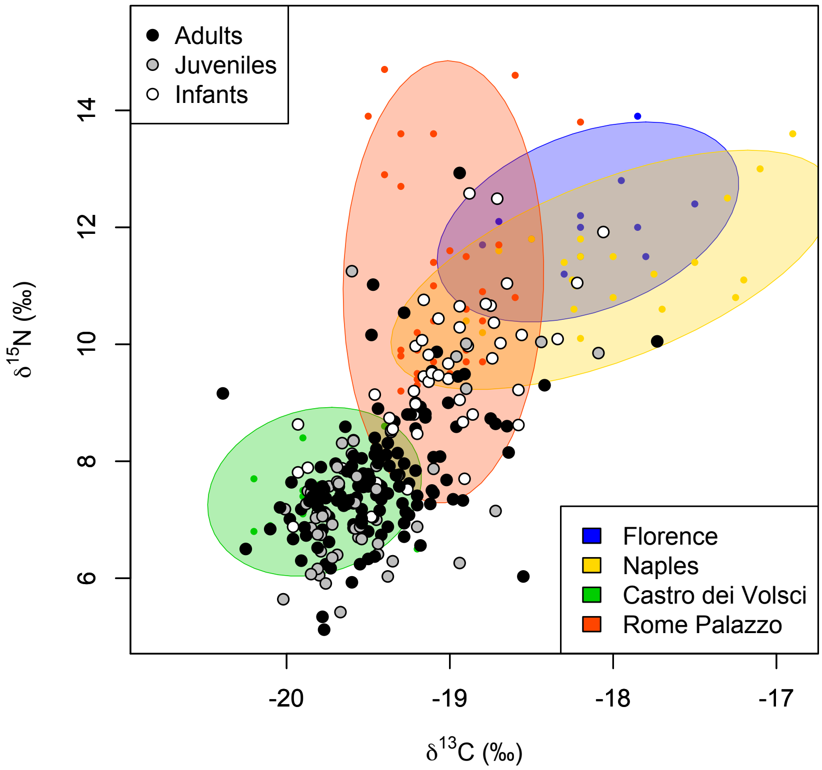

Figure 5.26: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for adults, juveniles and infants from Villamagna, compared to results from the Medici Princes, Florence, the Aragonese Princes, Naples (both from Fornaciari, 2008), and from the 14th-century sample from Palazzo della Cancelleria, Rome (Salamon et al., 2008). Also included for comparison are results from the 6th-century site of Castro dei Volsci (also by Salamon et al., 2008). Shaded area shows 95% confidence region for each site.*

medieval burial group discussed above) and VM4378 ($12 - 16$ year old juvenile from the early medieval period, 5.9‰). These low δ^{15}N ratios are similar to the animal range from Italian sites, and are therefore consistent with a largely herbivorous diet.

5.4.4 Villamagna in comparison to other sites

On average, individuals from Villamagna have intermediate δ^{13}C ratios compared to other Italian sites. Villamagna is significantly higher in δ^{13}C compared to Casale del Dolce and Castro dei Volsci ($p < 0.05$). Villamagna is significantly

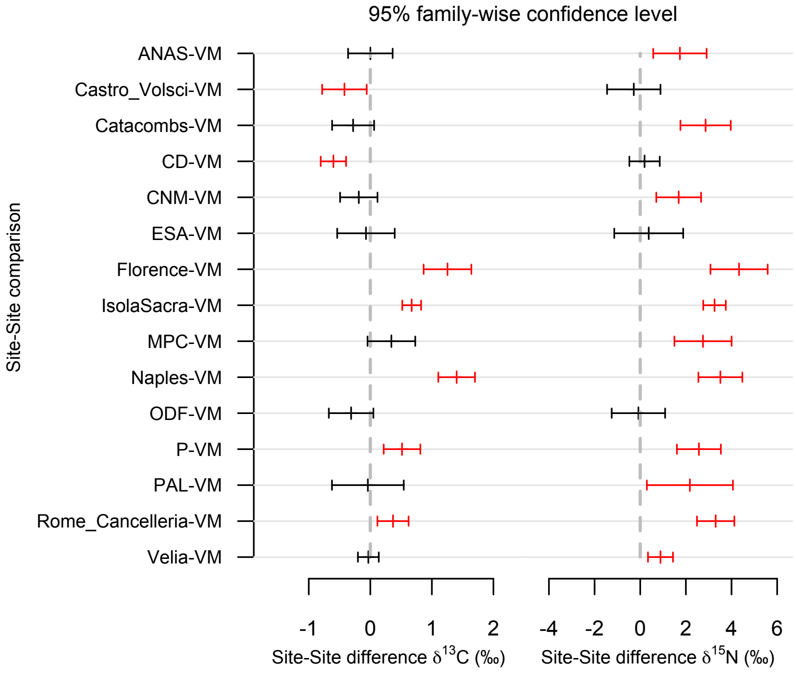

Figure 5.27: *Comparison of $\delta^{13}C$ and $\delta^{15}N$ between Italian sites and Villamagna, based on adult individuals only. The 95% confidence region is shown, calculated using a Tukey Honestly Significant Difference post-hoc correction to allow multiple comparisons. Those sites with significantly different isotopic ratios from Villamagna are highlighted in red. Site codes are as follows: Catacombs = Catacombs of St Callixtus (Rutgers et al., 2009); CD = Casale del Dolce (this study); CNM = Civitanova Marche (this study), ESA =Esanatoglia (this study); MPC = Marcellino e Pietro (this study); ODF= Osteria della Fontana (this study); P=Pompeii (this study); PAL= Palestrina (this study); Rome Cancelleria = Rome Palazzo della Cancelleria (Salamon et al., 2008); VM =Villamagna (this study).*

lower in δ^{13}C compared to Pompeii, Rome Palazzo della Cancelleria, Naples, Florence and Isola Sacra ($p < 0.05$). As mentioned above, Villamagna is statistically indistinguishable from Esanatoglia, the other Medieval site analysed for this study, and Osteria della Fontana, the nearby Roman site. Villamagna has one of the lowest average δ^{15}N values for Italy, and is significantly lower than CNM, Marcellino e Pietro, Pompeii, Palestrina, Rome Palazzo della Cancelleria, Naples, Florence, the Catacombs of St Callixtus, Velia, ANAS and Isola Sacra. For details see Figure 5.27 and Appendix B.1 and B.2. There is a large overall range in δ^{13}C and δ^{15}N, suggesting significant dietary diversity. Some individuals have isotopic ratios comparable to sites from Rome (see Figure 5.26). Some are similar to the Renaissance princes from Naples and Florence analysed by Fornaciari (2008). Others have δ^{13}C and δ^{15}N similar to contemporary fauna. Some of the isotopic variation is correlated to archaeological data, such as the tendency for individuals buried in or outside the Monastery part of the site to have higher δ^{15}N, and for sex-based differences in δ^{13}C (and to a less extent δ^{15}N. However, a large part of the isotopic variation is not explained by the available archaeological data.

5.5 Overall trends in Italian Isotopic Data

The remainder of this chapter will describe the analysis of patterns emerging from the Italian isotopic data. There is a large amount of isotopic variation within and between sites. From the discussion of results above, it appears that sites can be divided between those with high δ^{15}N (averaging greater than $> 9.0‰$) and those with low δ^{15}N (with averages $< 9.0‰$), see Figure 5.28. The majority of the high group seem to be coastal sites, while the majority of the low group seem to be inland (see Table 5.11 and Figure 5.30).

In the discussion above, it was clear that several Italian sites showed significant correlations between δ^{13}C and δ^{15}N, as did the Italian fauna. These are summarized in Figure 5.29. This figure shows all Italian sites with significant correlations (Pearson's $r > 0.30$, $p < 0.05$). A linear regression was calculated for δ^{13}C vs. δ^{15}N, and the equation of the regression line is plotted. The width of the line is proportional to the number of individuals at the site, and the sites are coloured according to Coastal/Inland. For reference, the regression line for δ^{13}C vs. δ^{15}N for Italian fauna is also plotted (see 5.1 above). The details of the calculations are in Table 5.12. It should also be noted that at many sites the correlation between δ^{13}C and δ^{15}N is based on only a small number of individuals. Such correlations can also be heavily influenced by outliers. This is

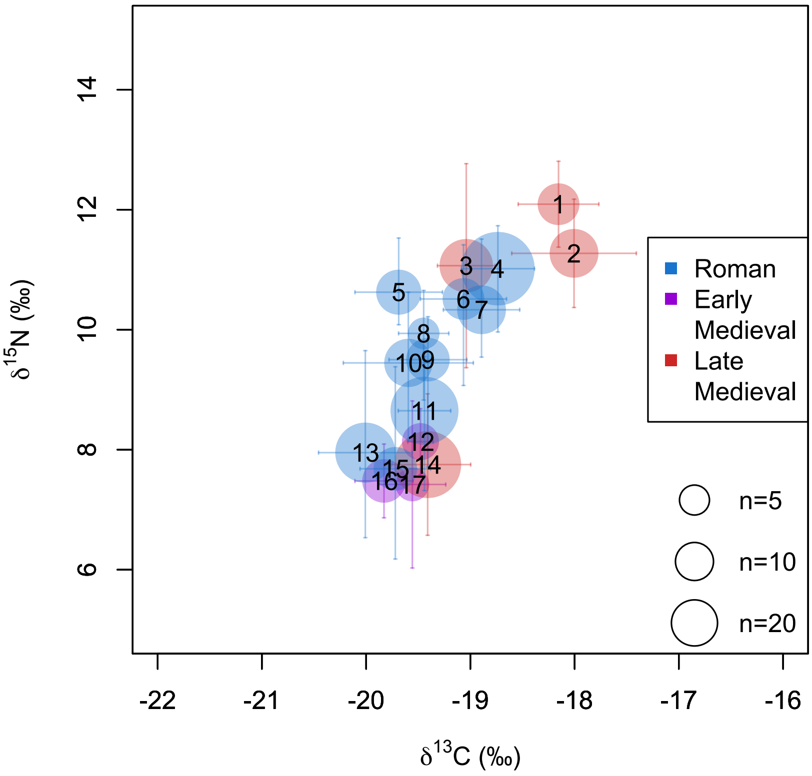

Figure 5.28: *Plot of average adult human $\delta^{13}C$ and $\delta^{15}N$ for all Italian sites, including previously published studies and new analyses presented here. Numbers refer to sites as follows: 1 - Florence (Fornaciari, 2008), 2 - Naples (Fornaciari, 2008), 3 - Rome Palazzo della Cancelleria (Salamon et al., 2008), 4 - Isola Sacra (Prowse et al., 2004; Crowe et al., 2010), 5 - Catacombs of St Callixtus (Rutgers et al., 2009), 6 - Marcellino e Pietro (this study), 7 - Pompeii (this study), 8 - Palestrina (this study), 9 - ANAS (Prowse et al., 2004), 10 - Civitanova Marche (this study), 11 - Velia (Craig et al., 2009), 12 - Esanatoglia (this study), 13 - Casale del Dolce (this study), 14 - Villamagna Late Medieval (this study), 15 - Osteria della Fontana (this study), 16 - Castro dei Volsci (Salamon et al., 2008), 17 - Villamagna Early Medieval (this study). Size of points is proportional to the square root of number of individuals sampled. Error bars illustrate the 1σ range for each site.*

Table 5.11: *Summary of Italian isotopic results for adults only: this study and previously published results. Newly analysed sites are marked (*). N is number of adults. C/I is Coastal/Inland. R/U is Rural/Urban (see below).*

Low δ^{15}N	N	C/I	R/U	δ^{13}C	1σ	δ^{15}N	1σ
Castro dei Volsci	14	I	R	-19.83	0.28	7.48	0.61
ODF*	14	I	R	-19.72	0.34	7.68	1.5
Villamagna*	110	I	R	-19.40	0.39	7.76	1.10
Casale del Dolce*	59	I	R	-20.01	0.45	7.95	1.42
Esanatoglia*	8	I	R	-19.48	0.12	8.13	0.55
Velia	117	C	U	-19.44	0.25	8.65	1.33
High δ^{15}N							
CNM*	21	C	U	-19.6	0.62	9.45	1.3
ANAS	14	I	R	-19.41	0.37	9.5	1.79
Palestrina*	5	I	U	-19.45	0.24	9.94	1.11
Pompeii*	22	C	U	-18.89	0.37	10.33	0.79
Marcellino e Pietro*	12	I	U	-19.07	0.41	10.51	1.44
St Callixtus	16	I	U	-19.69	0.42	10.63	0.54
Isola Sacra[a]	189	C	U	-18.74	0.35	11.02	1.05
Rome Cancelleria	33	I	U	-19.04	0.28	11.07	1.7
Naples	22	C	U	-18.01	0.6	11.27	0.9
Florence	12	C	U	-18.15	0.39	12.09	0.72

All values ‰

[a] Includes material from Prowse et al., 2004 and Crowe et al., 2010.

likely responsible for the observed relationship between δ^{13}C and δ^{15}N for the faunal samples, as inspection of Figure 5.2 above suggests. A few individuals have relatively high δ^{13}C and δ^{15}N, and a few have relatively low δ^{13}C and δ^{15}N while the rest show no relationship. This could be the result of trophic level effects due to the retention of a weaning signal (despite adult individuals having been sampled) or could be due to a covariance in δ^{13}C and δ^{15}N due to environmental differences (such as aridity).

Figure 5.29 illustrates that humans from coastal and inland sites have different intra-site relationships between δ^{13}C and δ^{15}N. Coastal sites tend to have lower slopes, closer to 1:1. Inland sites tend to have higher slopes, ranging from

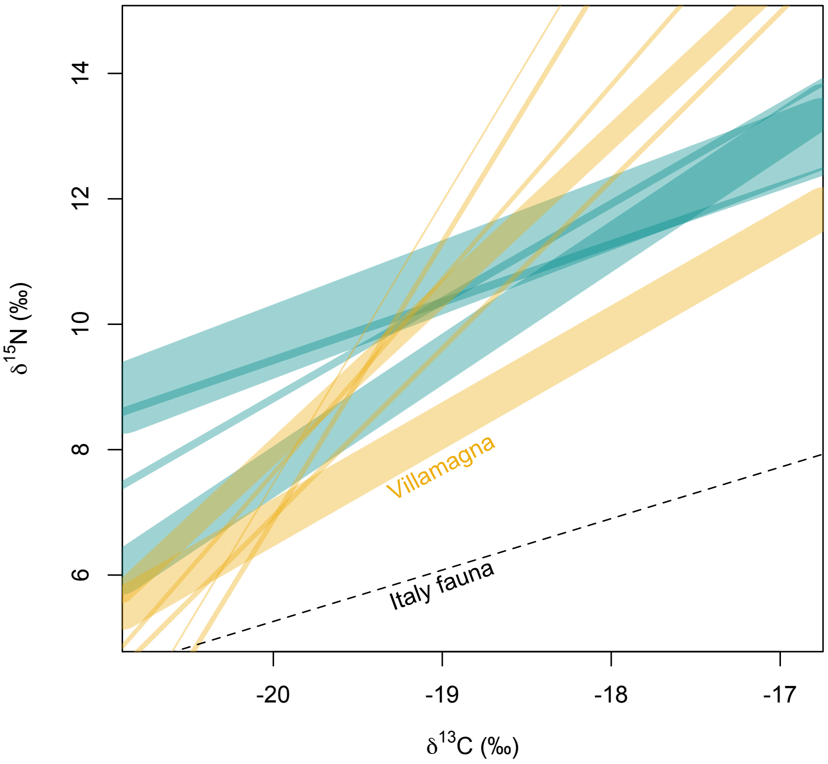

Figure 5.29: *Italian sites with significant correlations (Pearson's $r > 0.30$, $p < 0.05$), plotting the equation for the linear regression calculated for $\delta^{13}C$ vs. $\delta^{15}N$. The width of the line is proportional to the number of individuals at the site, and the sites are coloured according to Coastal/Inland. Villamagna (all periods) is treated as a single site. For reference, the regression line for $\delta^{13}C$ vs. $\delta^{15}N$ for Italian fauna is also plotted.*

1.3 for Villamagna to 4.4 for ANAS. A theoretical 100% marine diet may result in δ^{13}C of around −12‰, and δ^{15}N of around 18‰ (Richards and Hedges, 1999). This represents a roughly equal increase in δ^{13}C and δ^{15}N compared to a 100% terrestrial diet with endpoints around −21‰ and 8‰, and therefore a correlation between δ^{13}C and δ^{15}N with a slope of about 1 is consistent with increasing amounts of marine protein in the diet. The fact that this relationship is truer of humans from coastal Italian sites compared to humans from inland Italian sites suggests that variation in marine consumption is indeed a likely explanatory factor. However, this is highly dependent on the δ^{15}N of the theoretical 100% marine diet. As the review of fish isotopic evidence from the Roman and Medieval Mediterranean in section 6.1.6 will show, fish δ^{15}N ratios were relatively low, and it may therefore be expected that the slope between δ^{15}N and δ^{13}C in a population consuming variable amounts of marine fish in the Mediterranean would be even lower than 1:1. This suggests that variation in marine protein consumption is not the only explanatory factor (see Chapter 7). Where slopes of the relationship between δ^{13}C and δ^{15}N are higher, the correlation may still be partly due to underlying differences in marine food consumption, but could also reflect trophic level effects, since the expected increase in Δ^{13}C is 3–5 times smaller than the effect for Δ^{15}N.

Table 5.12: *Results of Pearson's Product Moment Correlation Calculation for correlation between δ^{13}C and δ^{15}N for Italian sites. Only sites with significant correlations are shown (Pearson's $r > 0.30$, $p < 0.05$). The slope for the regression for δ^{13}C vs. δ^{15}N is also shown.*

Site	CI	Date	N	mean δ^{13}C	mean δ^{15}N	R square	p	Slope
ANAS	I	R	14	-19.41	9.5	0.85	0.00000	4.42
CD	I	R	59	-20.01	7.95	0.63	0.00000	2.51
CNM	C	R	21	-19.6	9.45	0.55	0.00011	1.55
Isola Sacra	C	R	189	-18.74	11.02	0.11	0.00000	1.02
Marcellino e Pietro	I	EM	12	-19.07	10.51	0.78	0.00013	3.09
Naples	C	LM	22	-18.01	11.27	0.37	0.00245	0.92
ODF	I	R	14	-19.72	7.68	0.36	0.02222	2.68
Palestrina	I	R	5	-19.45	9.94	0.94	0.00560	4.49
Velia	C	R	117	-19.44	8.65	0.12	0.00018	1.8
Villamagna	I	LM	129	-19.44	7.73	0.28	0.00000	1.54

The exception is the medieval site of Villamagna, where the correlation was not large (R squared = 0.28), but the slope of the regression for δ^{13}C vs. δ^{15}N was 1.54. This slope is more similar to coastal sites than inland sites. Since the δ^{15}N values are on average much lower than coastal sites, it is unlikely this variation reflects a similar degree of marine fish consumption. Rather, it suggests that there is a similar relationship between δ^{13}C and δ^{15}N as at other inland sites, but in addition δ^{13}C values tend to be more variable (and higher) than at other sites. I discuss in Chapter 7 whether the variation in δ^{13}C at Villamagna may relate to the presence of C4 plants in the diet.

The main goal of this analysis was to determine the nature of chronological changes in isotopic ratios. In order to account for the possible confounding effects of factors such as sex and proximity to the coast, and in order to correct for random inter-site variation, mixed multi-level models (Maindonald and Braun, 2010) were constructed for δ^{13}C and δ^{15}N. In this model 'Early Medieval' individuals from Villamagna were treated in the category 'EM', while others were 'LM'. Only adult individuals were included. For details on these models see 4.5.2.

As expected given the large inter-site variation, random site-level differences account for approximately half of the overall variance (54% for δ^{13}C and 58% for δ^{15}N). The overall model suggests that there are significant differences between Roman and LM individuals for δ^{13}C, but not for δ^{15}N. Re-centring the model (see B.3) shows that the LM period has higher δ^{13}C compared to the Roman period (effect size 0.63‰, $p = 0.009$).

The Coastal–Inland differences produce a moderately significant effect for δ^{13}C of -0.57‰ ($p = 0.04$) for inland sites compared to coastal sites (see Figure 5.30). The effect for δ^{15}N for coastal-inland differences is not significant, although on average inland sites have lower δ^{15}N as expected (-0.81, $p = 0.34$). Sex has a significant effect on both δ^{13}C and δ^{15}N. The effect for males relative to females is $+0.14$‰ for δ^{13}C ($p = 0.002$) and $+0.40$‰ for δ^{15}N ($p = 0.008$). This takes into account random inter-site variation, and differences due to period and coastal proximity. Since sex is only known for approximately half of all adults from Italy, this effect is largely due to a few sites (Villamagna, Velia, Pompeii, Isola Sacra).

The discussion of Italian isotopic results above also indicated that the isotopic ratios from the royal families of Naples and Florence (Fornaciari, 2008) tend to be significantly higher compared to the rest of the region. The model

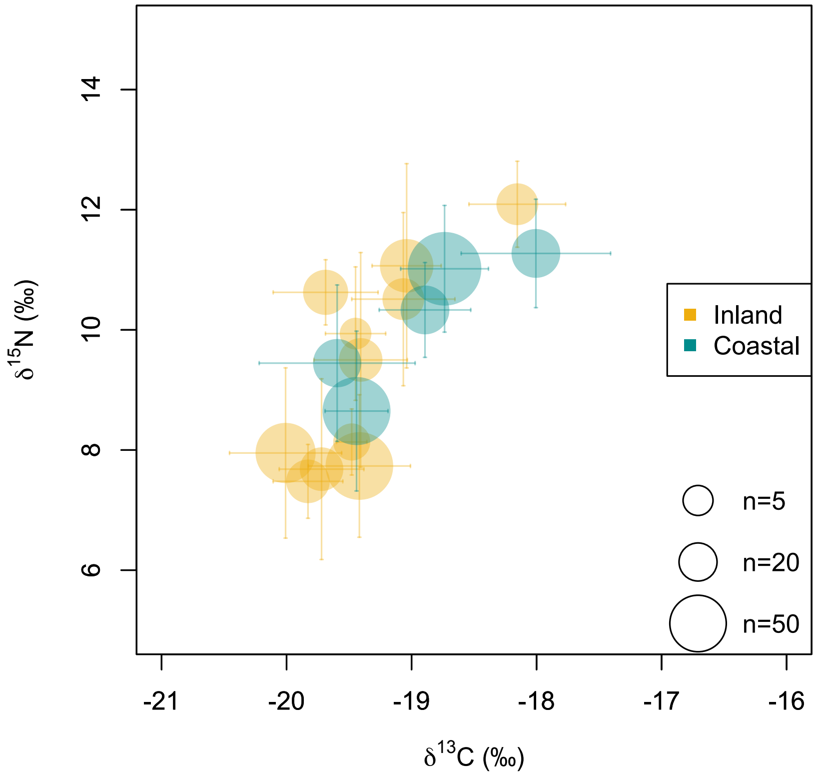

Figure 5.30: *Plot of average* $\delta^{13}C$ *and* $\delta^{15}N$ *for all Italian sites showing coastal/inland differences, including previously published studies and new analyses presented here. Villamagna EM and LM individuals are shown separately. Size of points is proportional to the square root of number of individuals sampled. There was a significant differences in* $\delta^{13}C$ *between Coastal and Inland sites (effect size* 0.57‰, $p = 0.04$, *but no significant difference in* $\delta^{15}N$. *Error bars shows the* 1σ *range for each site.*

was re-calculated with these sites removed (see B.3.2). This model suggests that these two sites were responsible for a large part of the contrast between different LM and Roman period, since the difference in δ^{13}C beween LM and Roman is not significant when these are removed (effect size 0.22‰, $p = 0.33$). These sites are also primarily responsible for the Coastal–Inland differences observed. Coastal-inland differences in δ^{13}C become only moderately significant (effect size -0.4‰, $p = 0.09$). The probability is reduced because the size of the effect is smaller and the number of degrees of freedom decreased. Coasta-inland differences in δ^{15}N are no longer significant with Naples and Florence removed ($p = 0.57$). The significance and size of the effect for sex remains largely unchanged.

The results above also highlighted that juveniles (individuals aged less than about 16, but old enough not to retain a weaning signal) may have slightly different isotopic ratios (usually lower in both δ^{13}C and δ^{15}N) compared to adults from the same site. This effect was tested using a similar model to that used above, but adding the 68 Italian juveniles to the dataset, and treating Agecat (A/J) as a fixed effect (see B.3.3). There is a significant effect for juveniles compared to adults for δ^{13}C of -0.16‰ ($p = 0.005$), but no significant effect for δ^{15}N ($p = 0.61$). Nevertheless, it should be noted that the majority (49 out of 68) of the juveniles come from Villamagna, and so this overall effect is largely due to the results from Villamagna.

Finally, it was observed that although there was a significant effect for δ^{13}C for Coastal/Inland sites, proximity to coast poorly predicted δ^{15}N values. This could have been because the three sites from Rome (the Catacombs of St Callixtus, Marcellino e Pietro and the Palazzo della Cancelleria) had high δ^{15}N, but were classified as inland because Rome is 25km from the sea. It seemed possible that urban vs. rural differences may account for the variation between sites better than Coastal/Inland differences. The designation of urban vs. rural was not systematic, but based on whether the burials could be associated with any type of city or town (see classifications in Table 5.11 above). It is true that the majority of rural sites are also inland. If we run an identical model to the main model above but substitute Rural vs. Urban (RU) for Coastal vs. Inland (CI), we note that the effect for RU is similar for δ^{13}C (effect size -0.70‰, $p = 0.005$), but much more significant for δ^{15}N (2.39‰, $p = 0.0002$). See B.3.4.

Similarly if Rural vs. Urban is included in addition to Coastal vs. Inland as explanatory factors, we observe that the significance of an effect in δ^{13}C for either of the two factors decreases ($p = 0.03$ for R/U and $p = 0.28$ for C/I), whereas for δ^{15}N there is a much larger and highly significant effect for Urban vs. Rural (effect size 2.70‰, $p = 0.0003$) compared to Coastal vs. Inland

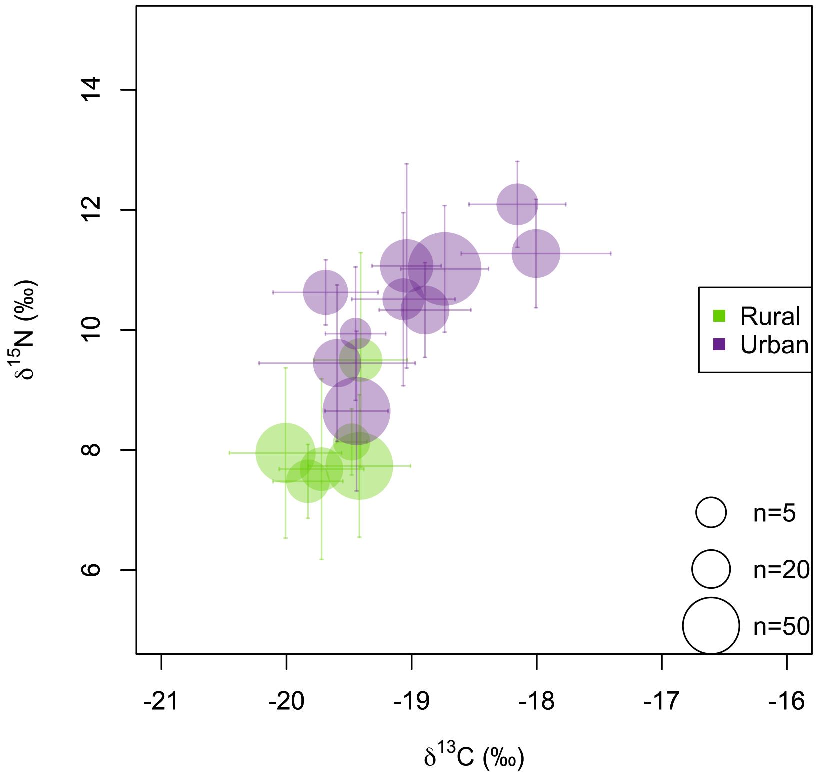

Figure 5.31: *Plot of average $\delta^{13}C$ and $\delta^{15}N$ for all Italian sites showing Rural/Urban differences, including previously published studies and new analyses presented here. Villamagna EM and LM individuals are shown separately. Size of points is proportional to the square root of number of individuals sampled. Error bars show the 1σ range for each site*

(effect size 0.62‰, $p = 0.29$). The differences between Rural and Urban sites are illustrated in Figure 5.31.

5.6 Summary of Results

5.6.1 Individual Sites

- The faunal δ^{13}C and δ^{15}N from Roman and Late Medieval contexts at Villamagna is similar to the fauna from the previously published Roman Italian sites of Isola Sacra and Velia. There is a large amount of intra-site variation for faunal specimens within Italy, and no evidence for consistent large-scale geographic effects.

- For humans, there is a large degree of inter-site variation, although a few pairs of sites are statistically indistinguishable in δ^{13}C and δ^{15}N, due largely to small sample sizes.

- The Roman coastal sites (Civitanova Marche and Pompeii) have similar δ^{15}N and δ^{13}C ratios to previously published coastal Roman sites (Isola Sacra, Velia).

- The inland Roman sites Casale del Dolce and Osteria della Fontana have lower δ^{13}C and δ^{15}N than the coastal Roman sites. However, at Casale del Dolce there is a high δ^{15}N group, similar to the high δ^{15}N previously noted at Velia (Craig et al. 2009).

- Roman Casale del Dolce and the previously published 6th century site of Castro dei Volsci, also located in inland Lazio, have significantly lower δ^{13}C compared to most other Italian sites (For Casale del Dolce, inter-site differences are between 0.3 and 2.0‰, $p < 0.05$ or less).

- The 6th to 8th-century site Esanatoglia, located in the Lombard-controlled Duchy of Spoleto, has similar δ^{13}C and δ^{15}N to all nearby Roman, Early Medieval and Late Medieval sites.

- The Early Christian crypt from Rome (Marcellino e Pietro) has high δ^{15}N and δ^{13}C similar to the Late Medieval samples from Palazzo della Cancelleria published previously (Salamon et al. 2008). It has significantly higher (+0.62‰) δ^{13}C compared to the individuals from the nearby catacomb of St Callixtus (Rutgers et al., 2009) dated a few centuries earlier ($p < 0.01$).

- At Medieval Villamagna, there are slightly significant differences according to phase, with the Late Medieval phase having slightly lower δ^{13}C compared to the Early Central Medieval phases. In addition, individuals buried on a N-S axis, including an unusual group buried in the Central

Medieval period apart from the other burials, have significantly higher δ^{15}N compared to those buried in W-E orientations.

- The adults from Villamagna all have relatively low δ^{15}N, comparable to inland Roman sites. There are some outliers from Villamagna with high δ^{13}C and δ^{15}N. Individuals buried around the Monastery part of the site tend to have higher δ^{15}N.

5.6.2 Overall Trends

- A mixed multi-level model of all adults from Italy with site as a random effect, and Date (Roman, Early Medieval, Late Medieval), Sex (Male, Female, Unknown), and Coastal/Inland as fixed explanatory variables shows that males tend to have slightly higher δ^{13}C (+0.14‰) and δ^{15}N (+0.4‰) compared to females, and that these differences are significant ($p = 0.002$ for δ^{13}C, $p = 0.008$ for δ^{15}N). However, sex was only reported for Villamagna, Velia, Pompeii and Isola Sacra, and this effect requires cautious interpretation.

- The same model suggests that Coastal/Inland differences account for a significant difference in δ^{13}C (effect size for inland sites is −0.57‰, $p = 0.04$), but the difference for δ^{15}N is not significant ($p = 0.33$).

- Taking into account the random inter-site variation, Coastal/Inland effects and variation due to sex, there are no significant differences between Roman, Early Medieval and Late Medieval Italian sites in δ^{15}N. Late Medieval individuals have significantly higher δ^{13}C compared to Roman adults ($p = 0.009$), but this difference disappears when the aristocratic individuals from Renaissance Florence and Naples are removed. Removal of these individuals also reduces the significance of the effect of δ^{13}C between coastal and inland sites.

- If the statistical model is re-run, including juveniles and using age category differences (A/J) as an explanatory variable, there is a small but significant effect for δ^{13}C (effect size for juveniles is $-0.15‰$, $p = 0.005$) but no significant effect for δ^{15}N ($p = 0.61$). Juveniles were only measured from five sites (Palestrina, Ctiviantova Marche, Esanatoglia, Villamagna, and the Catacombs of St Callixtus), so this result must be interpreted cautiously.

- When sites are re-classified as Rural or Urban, this explanatory variable results in a larger and more significant effect on δ^{15}N compared to Coastal/Inland differences (effect size for rural sites is $-2.4‰$, $p = 0.0002$). Interpretation of this result is limited by the manner of classifying sites into Rural/Urban categories. The explanatory power for R/U for δ^{13}C is similar to that of Coastal/Inland differences (effect size for rural sites is $-0.70‰$, $p = 0.005$). This suggests that in Roman and Medieval Italy individuals from urban areas have higher δ^{15}N, while individuals from coastal areas have higher δ^{13}C.

6

Stable isotopic evidence for Roman and Medieval diet: A meta-analysis of previous studies

Chapter 2 discussed the historical and archaeological evidence for diet change in Roman and Medieval Europe, focused especially on the evidence available for Italy. This qualitative description revealed both social and economic factors that could affect food behaviour. Social factors include the rise of Christianity and population movements from central Europe, which may have increased the social value of meat consumption. The changing economic patterns in Roman and Medieval Europe were also shown to have an influence on diet. The breakdown of trade infrastructure increased the reliance on local products in the Early Medieval period, decreasing the availability of bulk-imported foodstuffs. The decreased agricultural productivity and population density of the Early Medieval period may have resulted in more land being given over to pasture, with a larger per capita availability of meat as a result. The renewed intensification in agricultural production in the centuries c. AD 1000 brought a rise in population and trade, but potentially a decrease in the availability of animal meat as there was a renewed focus on large-scale cultivation.

This chapter compares the historical and archaeological overview discussed above with the range of evidence available from stable isotope palaeodietary reconstructions, through a summary and analysis of 121 previously studied human and faunal collections of data for Roman and Medieval Europe. In contrast to the overview provided by historical and archaeological techniques discussed in Chapter 2, stable isotope analysis provides a different scale of information about ancient diet, directly related to the individual's dietary choices. It is, however, limited by the caveats and assumptions discussed in Chapter 3.

As described in Chapter 4, the data are analysed using a mixed multi-level model similar in structure to the model used to describe variations within Italy in Chapter 5. First, variation in faunal isotopic ratios is examined across the study region. Then, variation between humans is examined. Factors such as regional and site-level variation are explored, as well as proximity to the coast, species, and sex. At the end of the chapter, the faunal-variability model is compared to the human-variability model.

6.1 Meta-analysis: Faunal variation in δ^{13}C and δ^{15}N

A dataset of domesticated herbivores (and pigs) was produced consisting of isotopic results for cattle, sheep/goat and pig from previously published sites.[1]. A total of 45 different herbivore collections were included in the database and were divided between four different regions: Central Europe, Mediterranean, Northern Europe and UK (specifically, England). If published studies contained faunal samples from a range of periods, only those dated AD 1–1500 were included. For example, this study includes only the Late Antique and Islamic samples from Ibiza (Fuller et al., 2010), omitting the earlier Punic samples.

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[1] N.B. pig are included but it should be remembered that they are omnivores

The average number of herbivores sampled per site was 12.7, with the smallest two sites being represented by a single individual (Weingarten and Hagerup) and the largest having 77 individual specimens (the Roman to Medieval faunal collection from York). On average, the faunal results are consistent with a mostly C3 diet, with a mean of all reported sheep/goat, cattle and pigs of $-20.8 \pm 1.2‰$. The average δ^{15}N was $6.4 \pm 1.9‰$.

Table 6.1: *Summary of meta-analysis domesticated herbivores/pigs, by location and species.*

Location	Species	N	δ^{13}C	1σ	max	min	δ^{15}N	1σ	max	min
CE	*Bos*	29	-21.54	0.52	-20.7	-22.8	5.68	1.17	8	3.56
	Ovicaprid	22	-21.38	0.49	-20	-22.07	6.48	1.92	11.2	3.3
	Sus	25	-21.18	0.75	-19	-22.4	7.09	1.56	9.5	3.87
Total CE		76	-21.37	0.61	-19	-22.8	6.38	1.64	11.2	3.3
Med	*Bos*	51	-19.67	1.5	-14.3	-22.6	6.24	2	10.3	2.5
	Ovicaprid	119	-19.76	0.9	-15.8	-21.7	5.92	2.14	12.9	2.6
	Sus	47	-20.12	0.97	-17	-21.5	6.19	2.35	11.7	2.5
Total Med		217	-19.81	1.09	-14.3	-22.6	6.05	2.15	12.9	2.5
NE	*Bos*	14	-21.82	0.58	-20.4	-22.6	6.23	0.8	7.4	4.5
	Ovicaprid	12	-21.58	0.44	-20.8	-22	6.81	0.48	7.76	6.2
	Sus	16	-21.42	0.64	-20.3	-22.5	7.4	1.51	9.6	4.5
Total NE		42	-21.6	0.58	-20.3	-22.6	6.84	1.16	9.6	4.5
UK	*Bos*	62	-21.74	0.47	-21	-23.9	5.84	1.41	10.4	3.5
	Ovicaprid	58	-21.64	0.33	-20.9	-22.3	6.3	1.57	10	2.7
	Sus	67	-21.55	0.55	-20.1	-22.8	7.71	1.63	12	4.6
Total UK		187	-21.64	0.47	-20.1	-23.9	6.65	1.74	12	2.7

All values ‰
N is total number of individuals

The differences between regions and species are summarized in Table 6.1. Approximately equal numbers of cattle, sheep/goat and pig were reported from each region, although the Mediterranean has notably more sheep/goat compared to the other two species. The map of sites with faunal samples (Figure

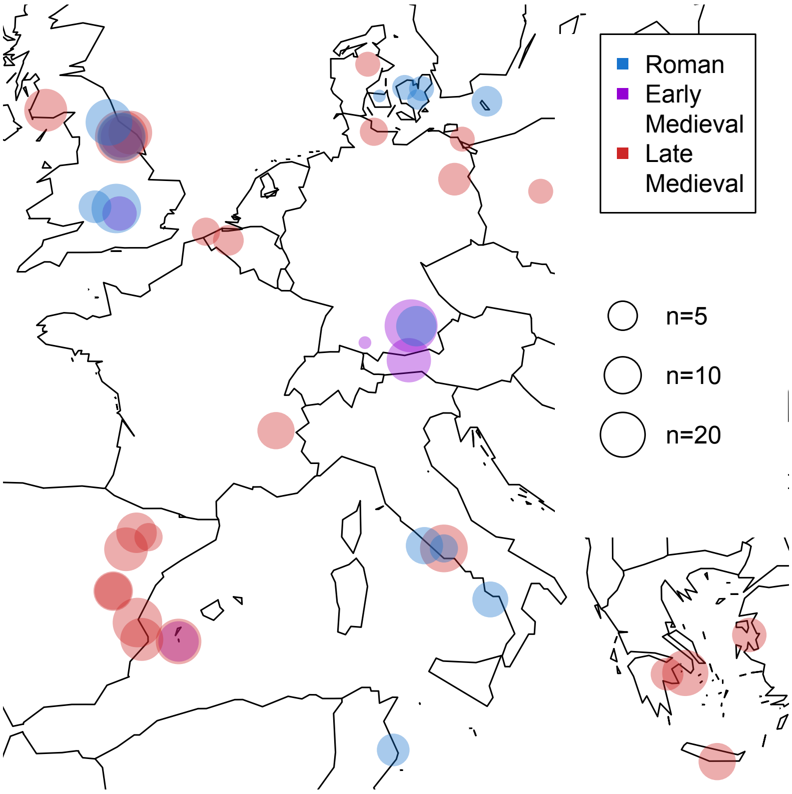

Figure 6.1: *Map showing location of sites, dates and number of domesticated herbivore/pigs samples included in the meta-analysis. The size of the point on the map is proportional to the square root of the number of individuals.*

6.1) shows how the number of faunal samples per site varies by location and date. Early Medieval specimens were particularly rare, with none from Northern Europe and only 12 from the Mediterranean (see Table 6.2). This reflects the relative frequency of studies from different regions and periods.

It must be remembered that the distribution of faunal species sampled for isotopic analysis and included in this database was never chosen to reflect the distribution of species represented on archaeological sites or in the human diet. In the case of the Mediterranean, however, historical and archaeological evidence suggests that a large consumption of sheep/goat products is plausible (see Chapter 2). In addition, these species are different sizes and the weighting of the isotopic averages for all species does not reflect the relative biomass that each individual would have contributed to the diet. If these counts were assumed to reflect actual numbers of individuals consumed, the amount of calories supplied by cattle would be underestimated relative to sheep/goat for example. It is not possible to do more than be aware of these biasing factors in the model, since any attempt to correct for them would introduce additional assumptions and potential error.

Table 6.2: *Summary of isotopic values for faunal samples included in the meta-analysis, by location and period.*

Location	Date	N	δ^{13}C	1σ	max	min	δ^{15}N	1σ	max	min
CE	R	12	-21.49	0.51	-20.2	-22	8.07	0.92	9.4	5.7
	EM	55	-21.42	0.62	-19	-22.8	6.27	1.52	11.2	3.56
	LM	9	-20.96	0.5	-20	-21.6	4.74	1.04	6.6	3.3
Med	R	27	-20.39	1.01	-18.3	-22.6	5.86	2.56	12.9	2.6
	EM	12	-20.08	0.74	-18.1	-21	5.89	1.38	8.7	4.2
	LM	178	-19.71	1.09	-14.3	-21.7	6.1	2.14	11.7	2.5
NE	R	14	-21.85	0.33	-21.3	-22.5	7.14	1.27	9.6	5.3
	LM	28	-21.47	0.64	-20.3	-22.6	6.7	1.1	9.5	4.5
UK	R	78	-21.63	0.43	-20.6	-22.8	6.87	1.68	10.4	3.8
	EM	20	-21.62	0.4	-20.9	-22.7	6.11	1.17	8.6	4.2
	LM	89	-21.66	0.51	-20.1	-23.9	6.59	1.87	12	2.7

All values ‰
N is total number of individuals

Table 6.3: *Summary of isotopic values for faunal samples included in the meta-analysis, by period.*

Date	N	δ^{13}C	1σ	max	min	δ^{15}N	1σ	max	min
EM	87	-21.28	0.77	-18.1	-22.8	6.18	1.42	11.2	3.56
LM	304	-20.48	1.29	-14.3	-23.9	6.25	1.99	12	2.5
R	131	-21.39	0.78	-18.3	-22.8	6.8	1.89	12.9	2.6

All values ‰
N is total number of individuals

Over a third of the faunal specimens in this dataset come from England (187/522). By comparison, the much larger Mediterranean region has 217 individuals. Central Europe and Northern Europe are more poorly represented, with 76 and 42 individuals respectively. Of the geographic regions, the Mediterranean appears distinct because of its higher faunal δ^{13}C, especially in the Late Medieval period, which is consistent with an increasing presence of C4 crops in the animal fodder. In addition, faunal samples from the Mediterranean seem to have lower δ^{15}N on average compared to other regions, although also more variability. The statistical validity of these observations will be discussed below. (See also 7.3.1 for a discussion of geographic and climatic influences).

6.1.1 Mediterranean fauna

The isotopic evidence for diet in the Mediterranean region is represented by several sites in Italy (discussed in Chapter 5), one in Tunisia (Keenleyside et al., 2009) and the work of two doctoral dissertations on Medieval Greece (Garvie-Lok, 2001), and Spain (Mundee, 2010). Although the results are considered for the Mediterranean as a whole, the potential diversity of isotopic systems within this large region is discussed in 7.3.1.

The 16 sites with faunal samples from the Mediterranean show higher δ^{13}C on average than any of the other areas studied. From Figure 6.2 it appears that the high δ^{13}C in fauna is largely confined to the Late Medieval sites. The difference in δ^{13}C could be partly climatic, but may also be due to the more frequent use of C4 crops in the Mediterranean, especially in the later Medieval period. The late Roman Tunisian site of Leptiminus (Keenleyside et al., 2009) has especially high average δ^{15}N compared to the rest, possibly due to climatic effects. Table A.10 summarizes the site averages from previously studied Mediterranean sites.

The only Early Medieval Mediterranean faunal collection comes from the Late Antique/Byzantine contexts at Ibiza (Fuller et al., 2010), where the average δ^{13}C for 7 sheep/goat, 2 pig, and 2 cattle was -20.1 ± 0.7‰, while the average δ^{15}N was 5.9 ± 1.4‰. The 13 Late Medieval faunal collections from Greece, Spain and Italy (this study) have site averages ranging from -21.3 to -18.1 ‰ (see Figure 6.2). They show a wide range in average δ^{15}N values,

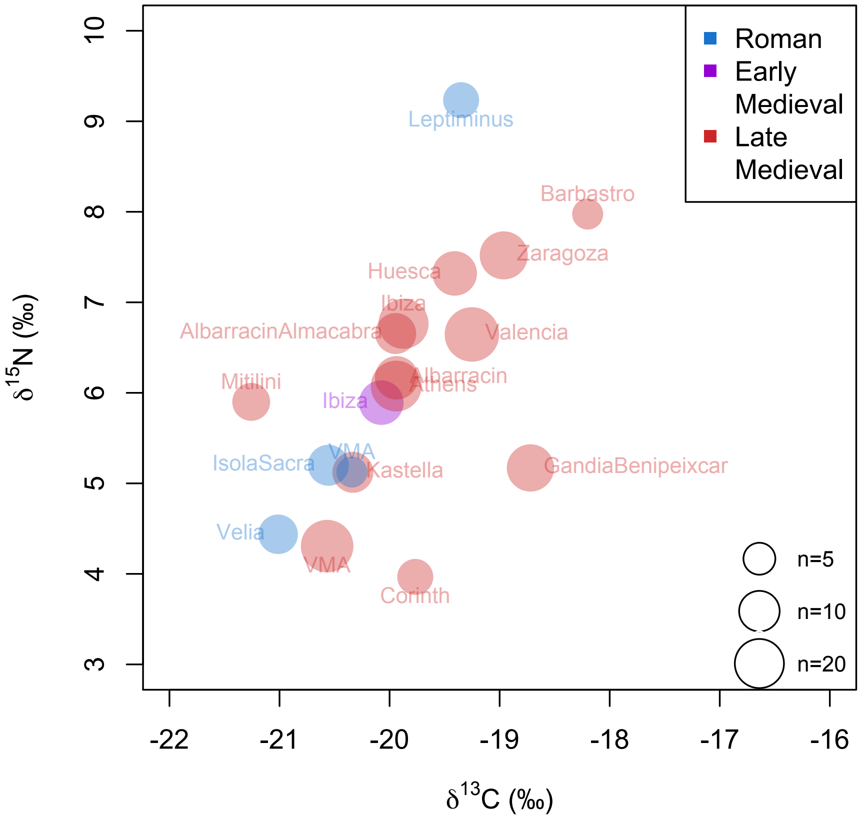

Figure 6.2: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for domesticated herbivores (cattle, pig, sheep/goat) from previously published sites from the Mediterranean. The size of the point is proportional to the square root of the number of individuals.*

from the 4.0 ± 0.8‰ reported for the 7 sheep/goat and cattle from 12th- to 13th-century Corinth to the 8.2 ± 0.3‰ for three sheep/goat from 11th-century Barbastro, Spain (Mundee, 2010). Many of the Spanish faunal samples have high δ^{15}N which could be due to the effect of aridity (see 2.5 and 7.3.1). In the case of Zaragoza the high average faunal δ^{15}N of 7.3 ± 2.1‰ suggest that aridity could be a factor, but the lower faunal δ^{15}N for Albarracin (5.8 ± 1.5‰) suggests such an effect is not consistent for all of Spain.

Given the moderately significant correlation between δ^{13}C and δ^{15}N noted for Italian fauna in Chapter 5, isotopic correlations for fauna across Europe were also investigated. Due to small sample sizes, faunal samples were pooled by Location and by Date. There were no significant correlations in faunal δ^{13}C

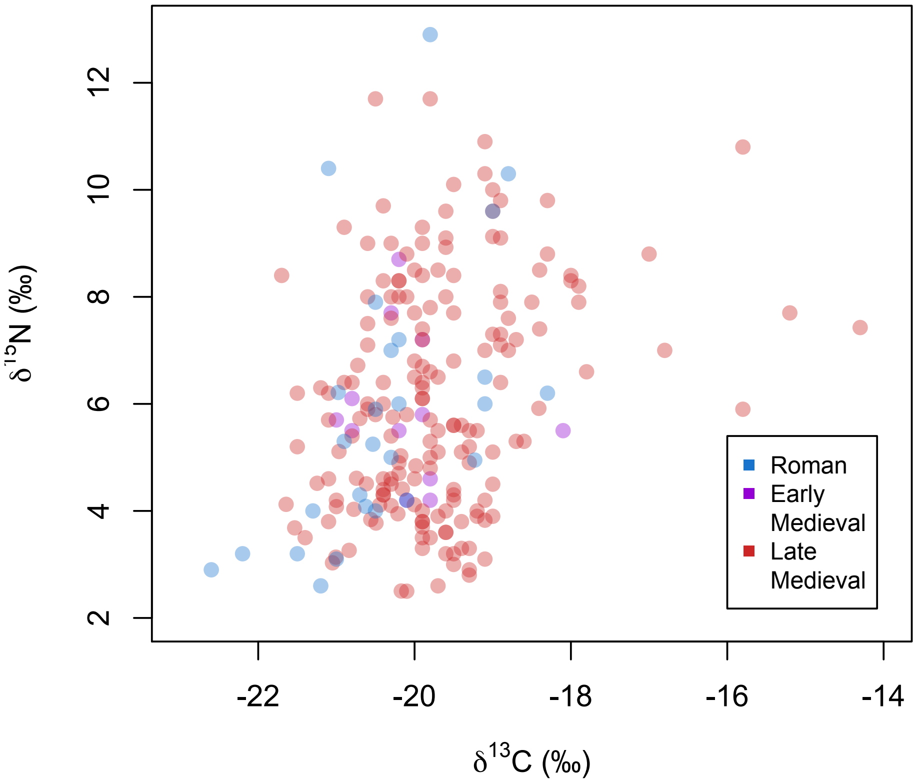

Figure 6.3: *Plot of all individual faunal $\delta^{13}C$ and $\delta^{15}N$ from previously published Mediterranean sites.*

and δ^{15}N by Date alone. The relationship between δ^{13}C and δ^{15}N is strongest for Mediterranean fauna on their own (see Figure 6.3), however the relationship is not strongly significant (R square = 0.08). Despite the appearance of a significant correlation of δ^{13}C and δ^{15}N based on site means alone (Figure 6.2 above), this correlation is not statistically significant at the site-level (Pearson's $r = 0.94$, $p = 0.2257$). If the Mediterranean is subdivided by country, the only significant faunal correlation is found in Italy, which was already discussed in Chapter 5. As discussed in Chapter 5, this may reflect a variety of factors that cause both δ^{13}C and δ^{15}N ratios to increase, such as environmental factors, and age-related trophic level effects.

6.1.2 Central European fauna

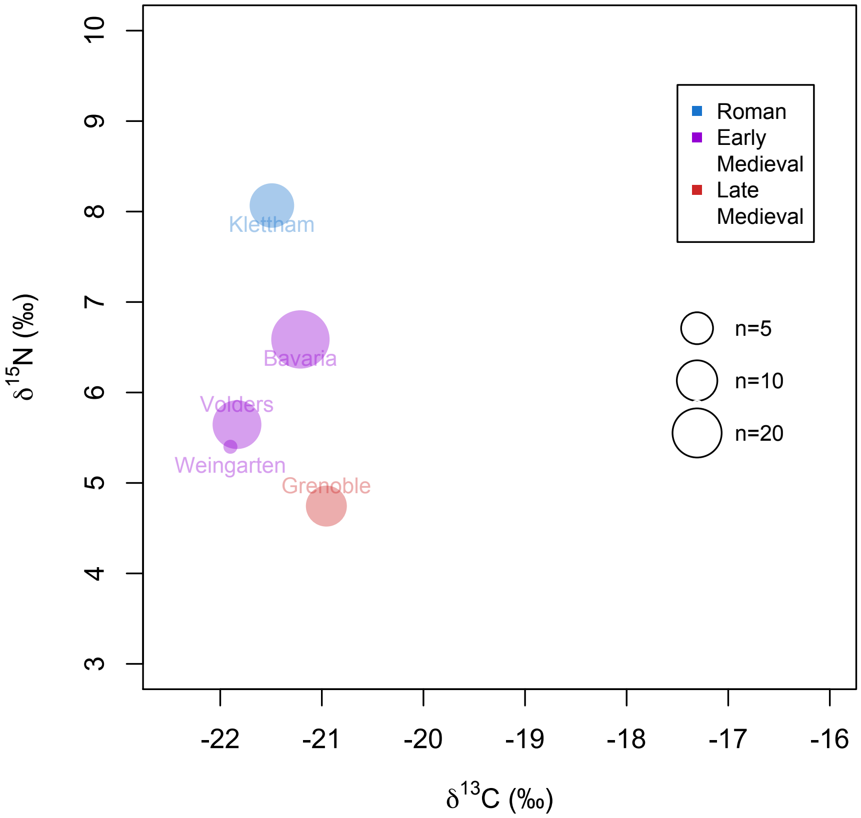

Figure 6.4: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for domesticated herbivores (cattle, pig, sheep/goat) from previously published sites from Central Europe. The size of the point on the map is proportional to the square root of the number of individuals.*

The faunal samples from Central Europe are from five separate collections (see Table A.11). The Early Medieval fauna from four separate Bavarian sites reported by Hakenbeck et al. (2010) were treated as a single site. The average δ^{13}C values reported range from -21.9 ± 0.49‰ for 19 sheep/goat, cattle and pigs from Early Medieval Austria (McGlynn, 2007) to -20.96 ± 0.5‰ for 9 sheep/goat, cattle and pigs from 13th- to15th-century Grenoble (Herrscher et al., 2001). This range of faunal values is consistent with C3 terrestrial δ^{13}C and much smaller than the range in Mediterranean faunal δ^{13}C noted above. The average δ^{15}N values reported are more variable, but because of the small number of sites it is impossible to make assessments about chronological

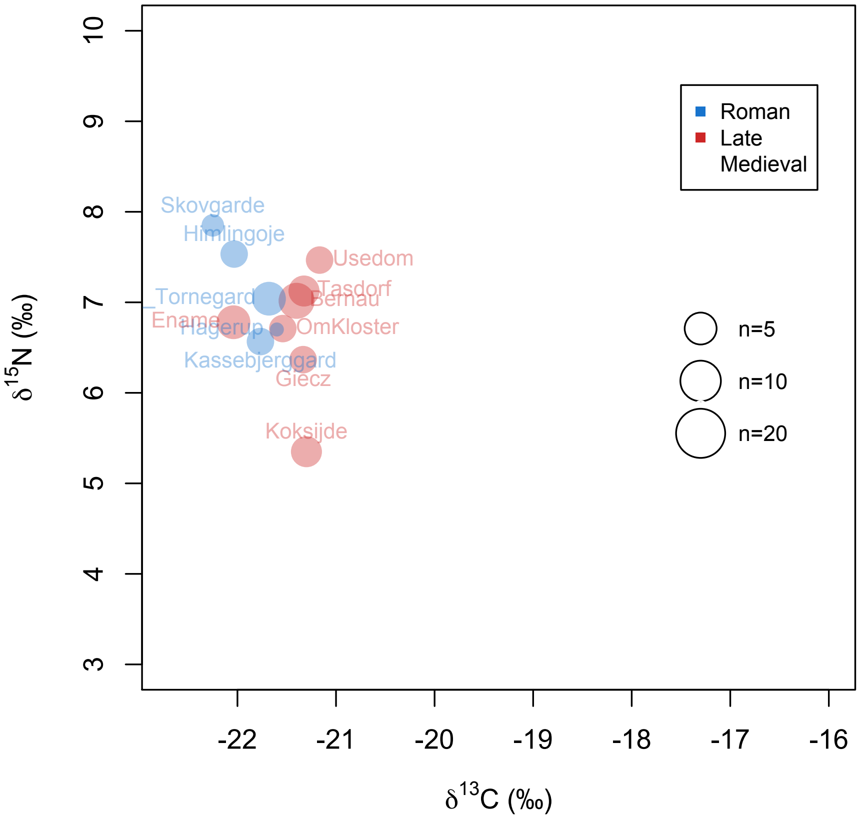

Figure 6.5: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for domesticated herbivores (cattle, pig, sheep/goat) from previously published sites from Northern Europe. The size of the point on the map is proportional to the square root of the number of individuals.*

variations in faunal isotopic ratios in Central Europe. The average δ^{15}N values reported range from 4.74 ± 1.03‰ for 13th- to 15th-century Grenoble to 7.30 ± 1.25‰ reported for 21 late Roman sheep/goat and cattle from Klettham in southern Germany (Hakenbeck et al., 2010). See Figure 6.4.

6.1.3 Northern European fauna

Northern European faunal δ^{15}N tends to be slightly higher than other areas (see Table 6.1 above and Figure 6.5), while δ^{13}C is generally consistent with a C3 terrestrial diet. A full list of sites can be found in Table A.12. The reported average δ^{15}N for the 12 sites from Northern Europe from all periods range from 5.35 ± 1.03 for the four Late Medieval herbivores from Koksijde, Belgium (Polet and Katzenberg, 2003) to $7.47 \pm 1.87‰$ for the three herbivores from Usedom, on the Baltic coast of Germany (Schäuble, 2005) also from the Late Medieval period. There are no faunal samples from the Early Medieval period, because a potential Early Medieval collection from Ridanäs on the island of Gotland, Sweden (Kosiba et al., 2007) was excluded.[2] See Figure 6.5.

6.1.4 Fauna from England

The 10 sites from Roman and Medieval England have faunal δ^{13}C averages in a terrestrial C3 range, with average δ^{15}N that can vary widely between sites (see Figure 6.6). The average δ^{13}C values from England show little difference in δ^{13}C, with the reported average values ranging from $-22.24 \pm 0.51‰$ for the 55 sheep/goat, pig and cattle from Early Medieval Shavard's farm (Hull, 2008) to -21.3 ± 0.51 for the 15 sheep/goat and cattle from Roman Astall (Cummings, 2008). A full list of sites from England can be found in Table A.13. Note that the English faunal sites have much smaller δ^{13}C variability compared to the similar number of individuals from the Mediterranean discussed above.

The δ^{15}N values are much more variable, with site averages ranging from a low of 5.9‰ for three sites (Berinsfield, St. Giles and Wharram Percy), and a high of 8.3‰ for the domesticated herbivores from medieval Whithorn. At Whithorn the pigs, included in the average, had much higher δ^{15}N compared to the other domesticated herbivores, consistent with an omnivorous diet.

6.1.5 Overall trends from faunal data

In order to test for the statistical significance of differences in faunal isotopic ratios through time and between different regions, the faunal data set was analysed using a mixed multi-level model. Site was considered a random effect, while Datecode (R, EM, LM), Loccode (Med, CE, NE, UK), Coastal/Inland,

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[2] The date of this site, from the 9th to the 12th centuries actually spans the cut off point of AD 1000 between Early and Late Medieval. The three cattle, sheep and pig from the site of Ridanäs have extremely high δ^{13}C values of $-16.57 \pm 0.45‰$. This combined with the high average δ^{15}N of $7.27 \pm 0.95‰$ suggested that marine foods may have been added to the animal fodder (Kosiba et al., 2007). There was no evidence for C4 plants in the area.

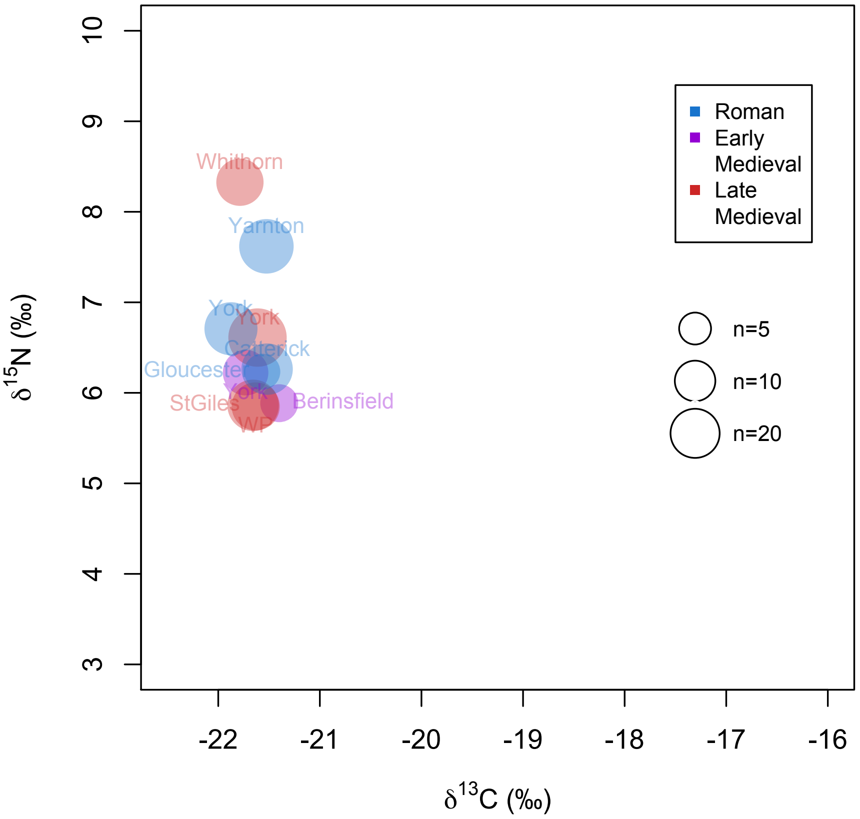

Figure 6.6: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for domesticated herbivores (cattle, pig, sheep/goat) from previously published sites from England. The size of the point on the map is proportional to the square root of the number of individuals.*

and Species (bos, ovicaprid, sus), were included as explanatory variables. As in Chapter 5, δ^{13}C and δ^{15}N were used as separate dependent variables (see Table 6.4).

For δ^{13}C, random site-level effects account for 35% of the total variance in the model, and account for 28% of the total variance for δ^{15}N. First, we observe that there are no significant differences in faunal isotopic ratios between Central Europe, Northern Europe or England. The Mediterranean can be distinguished by significantly higher δ^{13}C (effect size is 1.7‰, $p < 0.0001$):

If the statistics are re-calculated for each species independently, it is clear that the difference in Mediterranean δ^{13}C is consistent across all three species (see B.4.1). If the calculations are restricted to only the Mediterranean, there

Table 6.4: *Statistics for mixed effects model fitted by REML for fauna, calcualted for all periods, all regions.*

Model 1: Unsumplified

522 Observations, 41 Groups. AIC= 1183 (δ^{13}C), 2042 (δ^{15}N) . Random effect = Site
Fixed effects:

Date		δ^{13}C difference	p	δ^{15}N difference	p
Compared to EM	LM	0.16	0.28	0.51	0.14
	Roman	-0.08	0.63	0.72	0.07
Compared to Roman	LM	0.25	0.0542	-0.21	0.46
Location					
Compared to Med	NE	-1.84	< 0.0001	0.46	0.37
	England	-1.85	< 0.0001	0.33	0.55
	CE	-1.69	< 0.0001	0.14	0.85
Compared to CE	NE	-0.16	0.64	0.33	0.64
	England	-0.16	0.62	0.2	0.78
Compared to NE	England	-0.004	0.99	0.13	0.81
Coastal/Inland					
Compared to Coastal	Inland	0.28	0.19	0.24	0.6
Species					
Compared to cattle	Pig	0.16	0.04	1.22	< 0.0001
	Sheep/Goat	0.02	0.76	0.1	0.56
Compared to pig	Sheep/Goat	-0.14	0.07	-1.12	< 0.0001

are no significant differences between time periods (see B.4.2). The difference in δ^{13}C between the Mediterranean and other fauna is largely due higher δ^{13}C in Late Medieval fauna, especially from Spain as noted above. Climatic influences are possibly responsible and are discussed more fully in 7.3.1. As can be observed from the output above, there are no significant differences between any regions for δ^{15}N.

Due to the similarity between England, Central Europe and Northern Europe, it is appropriate to group these regions together (6.5). With the model simplified, other effects become more obvious. There are no significant differences in fauna depending on whether the site is coastal or inland (effect size for δ^{13}C $= 0.30$‰, $p = 0.15$; effect size for δ^{15}N$= 0.19$‰, $p = 0.66$). This is an appropriate result, since herbivore diet is not expected to be significantly influenced by the proximity to the coast. Cattle and sheep/goat are also not

Table 6.5: *Statistics for simplified mixed effects model fitted by REML for fauna, calcualted for all periods, all regions.*

Model 2: Simplified

Simplified Faunal model

522 Observations, 41 Groups. AIC= 1183 (δ^{13}C), 2042 (δ^{15}N) . Random effect = Site

Fixed effects:		δ^{13}C diff	p	δ^{15}N diff	p
Date					
Compared to EM	LM	0.14	0.33	0.55	0.1
	Roman	-0.1	0.54	0.76	0.047
Compared to Roman	LM	0.25	0.051	-0.21	0.46
Location					
Compared to Med	All others	-1.82	< 0.0001	0.37	0.39
Coastal/Inland					
Compared to Coastal	Inland	0.3	0.15	0.19	0.66
Species					
Compared to cattle	Pig	0.16	0.04	1.22	< 0.0001
	Sheep/Goat	0.02	0.76	0.1	0.55
Compared to pig	Sheep/Goat	-0.14	0.07	-1.12	< 0.0001

significantly different from one another (effect size for δ^{13}C = 0.02‰, $p = 0.76$; effect size for δ^{15}N = 0.10‰, $p = 0.55$). Pigs, however, are significantly higher in δ^{15}N compared to the other two species (effect size is 1.1‰ compared to ovicaprids and 1.2‰ compared to cattle, $p < 0.0001$ for both). Pigs are also slightly higher in δ^{13}C (for pigs vs. ovicaprids, effect size is 0.14‰, $p = 0.07$; for pigs vs. cattle, effect size is 0.16‰, $p = 0.04$). It must be remembered that these effects account for random inter-site differences, and differences between regions and time periods.

The simplified comparison also brings out significant differences within the faunal dataset by period. Roman and Late Medieval periods have similar δ^{15}N, but late Medieval faunal samples have significantly higher δ^{13}C (effect size is 0.25‰, $p = 0.05$). The Early Medieval faunal samples also have lower δ^{15}N compared to the other two periods, (effect size 0.55‰ compared to Late Medieval, and 0.76‰ compared to Roman), differences which are only moderatly significant ($p = 0.10$) compared to Late Medieval, but significant ($p = 0.046$) compared to Roman. The differences between species and between

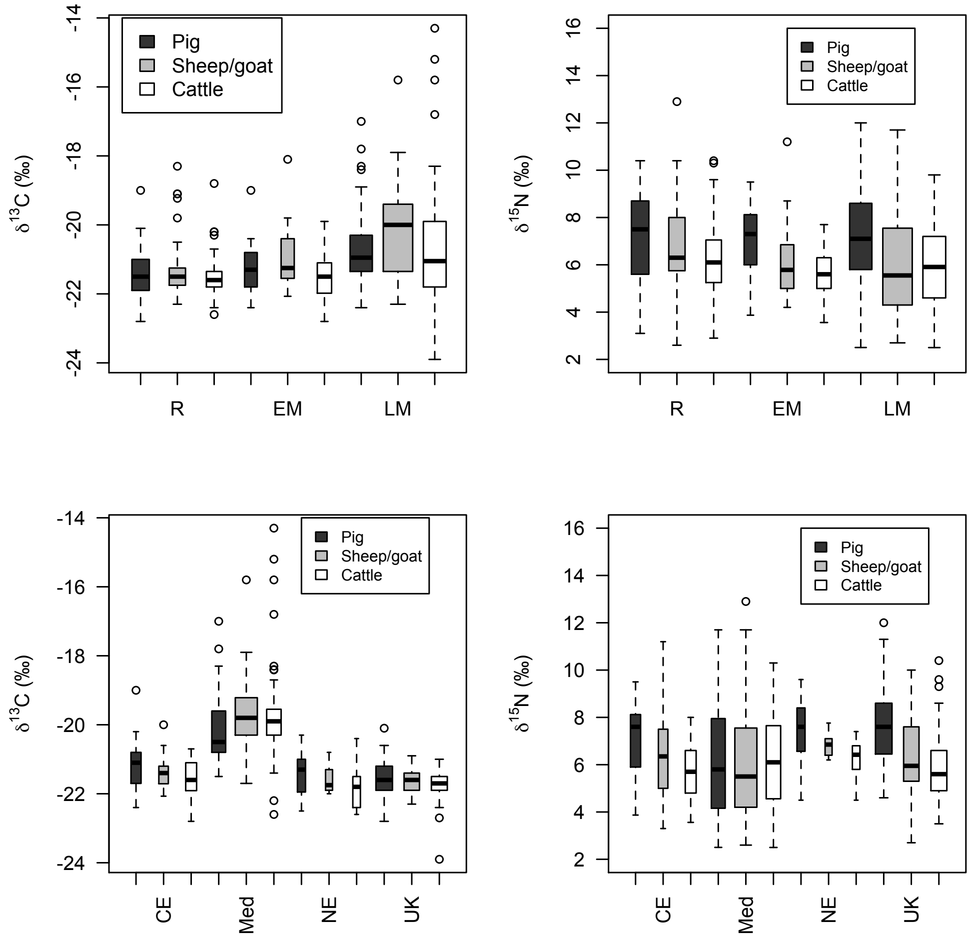

Figure 6.7: *Box plot summaries of $\delta^{13}C$ and $\delta^{15}N$ for fauna from the meta-analysis, by period and location. Box width is proportional to the square root of the number of individuals.*

regions for different periods are summarized in Figure 6.7. Note, however, that the figures are only able to summarize the effects of two factors at a time, whereas the statistical model takes into account the effect of multiple factors (Date, Coastal/Inland, Location, Species), as well as random inter-site variation. Therefore while the figures provide a visual summary of the data, they are a simplification of more complex trends, which are considered in the statistical model. The differences between periods are not significant when species are considered separately, due to the smaller sample sizes (see B.4.1).

6.1.6 Marine fish comparison

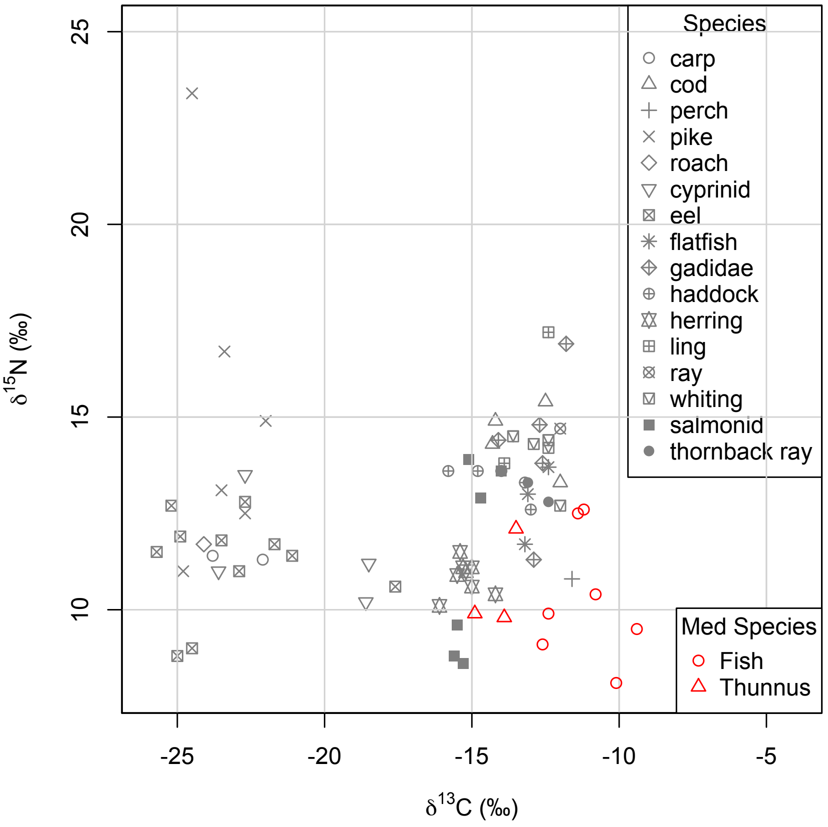

Figure 6.8: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for fish recovered from previously published Roman and Medieval archaeological sites*

Figure 6.8 data collected as part of the meta-analysis included archaeological marine fish samples from Medieval Spain (Mundee, 2010) and Roman Italy (Craig et al., 2009). These were plotted alongside the available Roman and Medieval fish data from Northern Europe, Central Europe and England, which includes both freshwater and marine fish. The Mediterranean fish have δ^{13}C equal to or exceeding the highest δ^{13}C from the rest of Europe. The difference between the Mediterranean and other seas lies in the δ^{15}N ratios, which is apparent even in the limited amount of data currently available. The average δ^{15}N from the Mediterranean fish shown here is 10.4‰, compared to 12.7‰ for non-

Mediterranean fish.[3] This difference is significant ($t(56) = -3.54$, $p < 0.001$). Mediterranean fish are slightly lower on average in δ^{15}N, but δ^{15}N is highly variable in both groups and samples are not necessarily representative. Similar δ^{13}C (around −12‰) and δ^{15}N (around 10‰) were reported by Vika and Theodoropoulou (2012) for marine species from Neolithic-Classical period sites from the Aegean, suggested the lower δ^{15}N for the Mediterranean is consistent through time. These differences highlight the need for further comparison of archaeological fish isotopic ratios, and emphasize that the estimate for the δ^{15}N of a theoretical 100% marine diet should be lower in the Mediterranean than elsewhere.

6.2 Meta-analysis: Human variation in δ^{13}C and δ^{15}N

In total, 2726 individuals were included in the database, from 101 different sites. The average number of humans analysed per site was 27. The largest collection of humans were the 189 humans from Roman Isola Sacra reported by Prowse et al. (2004) and Crowe et al. (2010). The differences between the human results from different regions are shown in Table 6.6. See Figure 6.9 for a map of the samples included, by date.

The number of humans included from each period is roughly equal (see Table 6.7), but there are differences between different regions. The largest group in the database come from the Mediterranean (1153/2726) and from England (1049/2726). Central Europe and Northern Europe are represented by fewer specimens. The humans from Central Europe are almost entirely from the Early Medieval period, while Northern Europe is represented by only nine Early Medieval individuals.

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[3] This includes only marine fish with $\delta^{13}\text{C} > -20‰$.

Table 6.6: *Summary of humans for meta-analysis, by location and period*

Location	Date	N	δ^{13}C	1σ	max	min	δ^{15}N	1σ	max	min
CE	R	10	-19.32	0.81	-17.1	-19.9	9.45	0.58	10.9	8.8
	EM	302	-19.75	0.55	-16.8	-23.6	9.63	0.88	12.85	5
	LM	34	-19.95	0.38	-19.1	-20.6	8.68	0.92	10.8	6.3
All CE		346	-19.76	0.55	-16.8	-23.6	9.53	0.92	12.85	5
Med	R	523	-19.07	0.73	-16.5	-20.74	10.08	1.95	15.7	5.7
	EM	95	-19.19	0.57	-16	-20.2	9.70	1.86	14.1	5.9
	LM	491	-18.62	1.04	-13.1	-20.17	9.85	1.76	17.13	5.16
All Med		1109	-18.88	0.9	-13.1	-20.74	9.95	1.86	17.13	5.16
NE	R	70	-20.51	0.33	-19.9	-22.4	10.96	0.61	12.600 1	0.1
	EM	9	-19.93	0.4	-19.4	-20.5	10.01	1.42	11.7	8
	LM	99	-19.42	0.58	-18	-20.6	10.53	1.34	13.4	7.9
All NE		178	-19.87	0.72	-18	-22.4	10.67	1.14	13.4	7.9
UK	R	249	-19.58	0.74	-15.8	-20.9	10.68	1.17	14.8	6.7
	EM	499	-20.07	0.54	-18.2	-22.12	9.69	1.28	13.64	4.34
	LM	315	-19.33	0.7	-16.5	-21.1	12.08	1.58	17.2	6
All UK		1063	-19.74	0.72	-15.8	-22.12	10.63	1.69	17.2	4.34

All values ‰

N is total number of individuals

Table 6.7: *Summary of humans for meta-analysis, by period*

Date	N	δ^{13}C	1σ	max	min	δ^{15}N	1σ	max	min
R	840	-19.34	0.83	-15.8	-22.4	10.32	1.7	15.7	5.7
EM	911	-19.86	0.61	-16	-23.6	9.7	1.23	14.1	4.34
LM	961	-19.01	0.96	-13.1	-21.1	10.56	1.99	17.2	5.12

All values ‰

N is total number of individuals

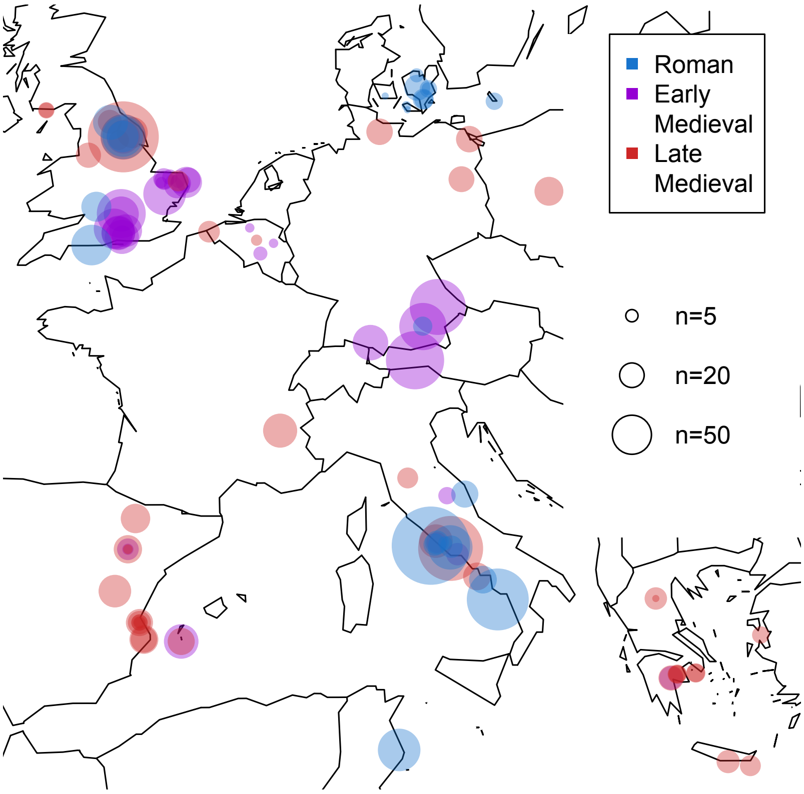

Figure 6.9: *Map showing location of sites, dates and number of samples for humans included in the meta-analysis. The size of the point on the map is proportional to the square root of the number of individuals.*

6.2.1 Mediterranean humans

The meta-analysis for humans included 46 different sites from the Mediterranean.[4] Similar to the faunal samples, humans from the Mediterranean appear to have higher δ^{13}C. The average δ^{13}C for all individuals from the Mediterranean was −18.9‰, which is 0.8 to 0.9‰ higher than the other three regions on average. This is consistent for all periods, with Late Medieval humans from the Mediterranean having the highest average δ^{13}C (mean = −18.7‰; see Figure 6.10). A full list of sites is included in Table A.14.

The Roman material from the Mediterranean includes only one site outside of Italy, the late Roman individuals from Leptiminus, Tunisia (Keenleyside et al., 2009). Compared to the Italian material already discussed in Chapter 5,

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[4] The number of sites is artificially high because the subdivisions within Late Medieval Spanish sites in Mundee (2010) were maintained.

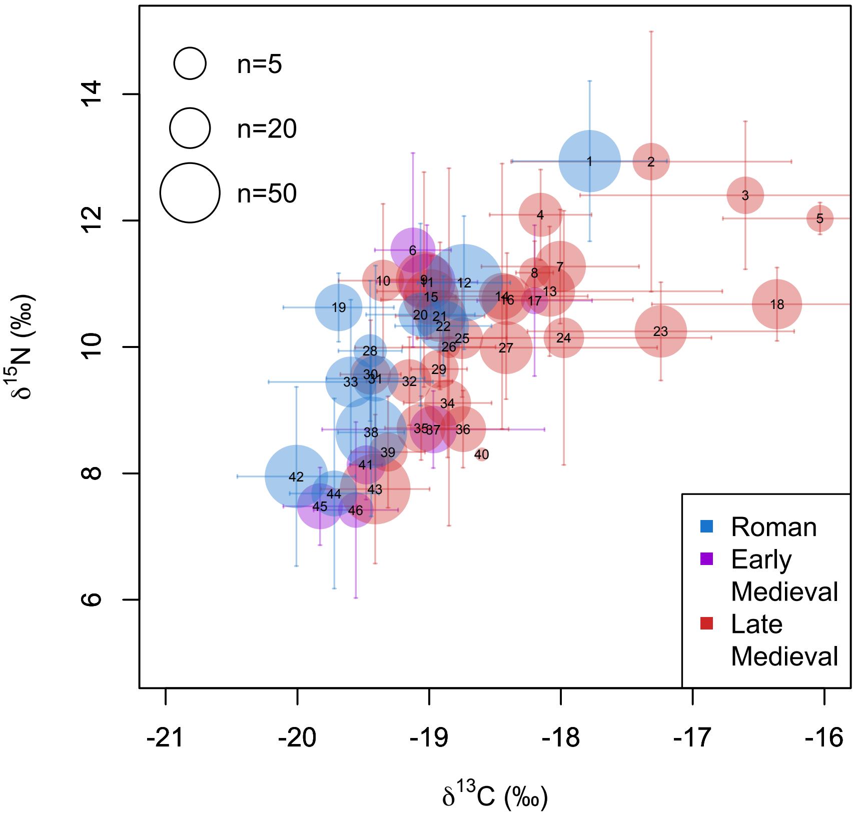

Figure 6.10: *Plot of mean $\delta^{13}C$ and $\delta^{15}N$ for humans (adults) from previously published sites from the Mediterranean. The size of the point is proportional to the square root of the number of individuals. Error bars show 1σ range for each site. For identification of sites see Table 6.8*

Table 6.8: *Legend key for Figure 6.10*

1-Leptiminus	2-Valencia Amoina	3-Valencia Calle Sagunto
4-Florence	5-Valencia Calle Pintor	6-Zaragoza Predicadores
7-Naples	8-Valencia San Andres	9-Rome Cancelleria
10-Agora Hephaisteion	11-Ibiza	12-Isola Sacra
13-Ibiza	14-Valencia San Vicente	15-Albarracin Almacabra
16-Valencia Calle Alta	17-Zaragoza Roman Theatre	18-Gandia Benipeixcar
19-Catacombs	20-MPC	21-Zaragoza Babal-Qibla
22-P	23-Gandia Colegiata	24-Corinth Ottoman
25-Corinth Frankish	26-Zaragoza La Seo	27-Jaca Plaza Biscos
28-PAL	29-Corinth Ruined Church	30-Agora Ayios Nicolaos
31-ANAS	32-Petras	33-CNM
34-Kastella	35-Nemea Medieval	36-Servia
37-Nemea Early Christian	38-Velia	39-Mitilini Gatteliusi
40-Athens	41-ESA	42-CD
43-VM LM	44-ODF	45-Castro dei Volsci
46-VM EM		

humans from Leptiminus have extremely high average δ^{13}C (−17.8‰) and δ^{15}N (12.9‰). The faunal samples from this site were noted above for their higher δ^{15}N, and the effect of aridity cannot be ruled out (see 7.3.1). The site was known in Antiquity for the quality of its garum, and the large fish processing facilities that were excavated suggested that marine resources were important to the economy of the inhabitants (Keenleyside et al., 2009). The highest human δ^{15}N and δ^{13}C values come from the latest phases of occupation, from the late 4th and 5th century, around the time of the Vandal conquest of North Africa. The fact that δ^{15}N values in the latest phase of occupation of the site were the highest of all the phases suggested to the authors that an increase in marine food consumption may have occurred as a result of the confiscation of land that took place after the Vandals began ruling Africa in the 5th century, which could have decreased the availability of livestock. This explanation is plausible, although when I re-calculate the differences based on only adult δ^{15}N and δ^{13}C values, including all the burials dated from the 4th to 6th centuries, there are no significant differences between early or late periods.

Four Early Medieval sites from outside Italy were included in the database. Two are of relatively early date: 4th- to 7th-century Ibiza (Fuller et al., 2010) and 5th- to 6th-century Nemea (Garvie-Lok, 2001). The two subsets from Zaragoza (Mundee, 2010) date to the end of the Early Medieval period (9th- to 10th-century). The three individuals from Zaragoza Roman Theatre have especially high average δ^{13}C (−18.2‰).

Within the Mediterranean region, humans from the Late Medieval period have the highest δ^{13}C, with an average of −18.7‰ for 28 sites. From Figure 6.10, it is clear that five LM Mediterranean sites have especially high average δ^{13}C for humans. These are all collections from Gandia and Valencia, reported by Mundee (2010). Mundee's interpretation of these high δ^{13}C ratios was that they reflected marine protein consumption and/or C4 plants in the diet, since both are located near the coast. As discussed above, the faunal values from the Mediterranean were also high in δ^{13}C, especially those from the Late Medieval period. This suggests that climatic/geographic effects may be partly responsible, but this would not explain the range in δ^{13}C observed at these sites.

A large number of humans from Late Medieval sites in the Mediterranean come from Greece, the result of work by Garvie-Lok (2001). The ten sites that were analysed as part of that study focused on Late Medieval population changes, from Greek Orthodox to Frankish to Ottoman. Greek Orthodox populations were expected to have substantially higher fish consumption than Frankish populations, who were thought to have consumed more meat. Contrary to expectations, the study found that populations of all time periods, whether they were coastal or inland, had high δ^{15}N with little increase in δ^{13}C, indicating a diet based largely on terrestrial resources, with large amounts of animal protein. There were no substantial differences between Frankish and Greek Orthodox populations. Garvie-Lok noted that there was an increase in C4 consumption, probably millet, in the city of Corinth following a 14th century attack by the Catalans. She also found especially high δ^{13}C values for the Ottoman period samples, consistent with historical evidence for an increased reliance on maize during this period, although these results are not included in this meta-analysis, since they date after the end of the 15th century. A more recent study by Bourbou and Richards (2007) examined 26 individuals from the 11th-century site of Kastella in the city of Heraklion on Crete. They interpreted the higher human δ^{15}N ratios as the result of a large amount of animal meat consumption, as well as marine fish consumption for some individuals. They found no overall sex differences, and concluded that the diet was generally terrestrial and C3-based.

6.2.2 Central European humans

Of all the geographic regions, the lowest human δ^{15}N values have been reported from the five central European sites (see Table A.15 and Figure 6.11). The hu-

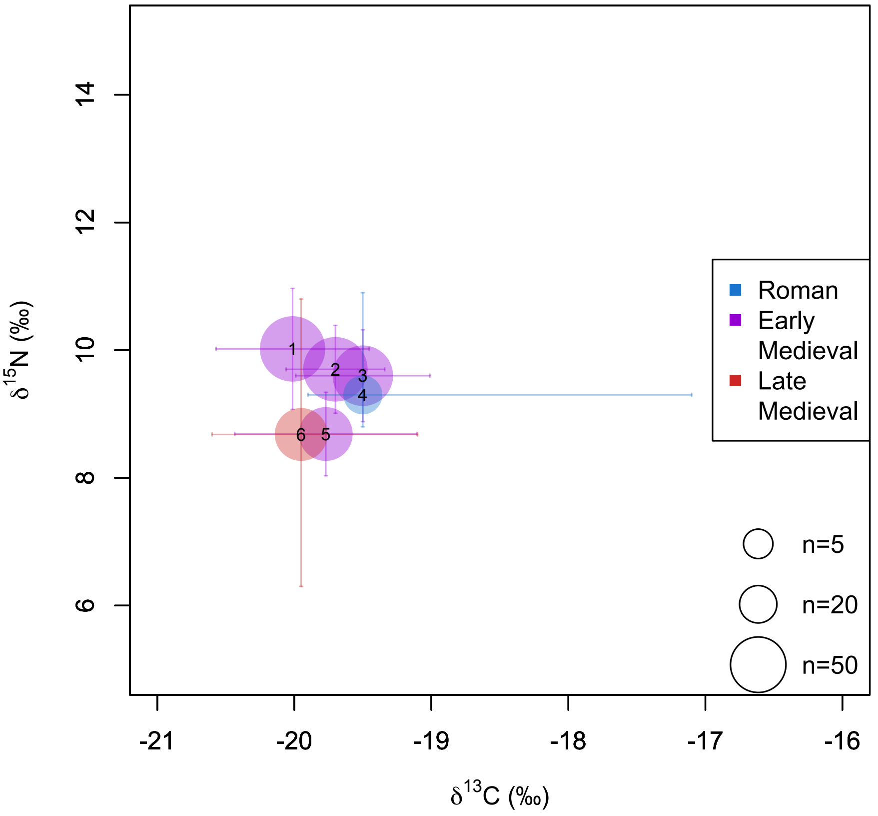

Figure 6.11: *Plot of mean* $\delta^{13}C$ *and* $\delta^{15}N$ *for humans (adults) from previously published sites from Central Europe. Point size is proportional to the square root of the number of individuals. Error bars show* 1σ *range for each site, except for sites 2, 3 and 4 are plotted as medians and ranges. Sites are as follows: 1 - Volders, 2 - Altenerding, 3 - Straubing-Bajuwarenstrasse, 4 - Klettham, 5 - Weingarten, 6 - Grenoble*

man δ^{15}N values from central Europe are lower than any other region, perhaps because all of the central European sites are located a significant distance away from the coast, unlike some of the sites in other regions. However, freshwater fish resources were a potential high δ^{15}N food, which would have been available but perhaps not exploited. McGlynn (2007) studied 153 individuals from a 5th- to 7th-century site in the Austrian Alps and concluded the diet was strictly based on C3 terrestrial plant and animal foods, despite the proximity of many freshwater lakes and rivers for fish.

The average δ^{13}C values range from -20.01‰ for Volders, Austria to -19.4

for Early Medieval Altenerding (Hakenbeck et al., 2010) where the range in δ^{13}C was -20.3 to -16.8‰. Hakenbeck et al. (2010) examined three sites in Late Roman (Klettham) and Early Medieval (Straubing-Bajuwarenstrasse and Altenerding) Bavaria, and found that there was no significant change in diet through time. The range in δ^{13}C was predominantly C3 terrestrial, with a median around -19.5‰. The highest δ^{13}C values for the Roman and Medieval period were -17.1‰ and -16.8‰, indicating the presence of a C4 plant in the food chain, even in the Roman period. To avoid a skewed average, the authors reported the medians and the range of their human samples. The highest faunal δ^{13}C ratios from the study are only -19.0‰ for the Early Medieval period and -18.8‰ for the Roman period, so the variation in human δ^{13}C is not explained by the animal variation.[5] It is possible that these humans represent immigrants from an area where more C4 plants were commonly grown.

The potential presence of C4 crops was also detected in southern Germany in another study. Schutkowski et al. (1999) analysed trace elements (Ca, Sr, Ba, Zn, Cu) and stable isotopes in individuals from the Early Medieval cemetery of Weingarten in southwest Germany. Their stable isotope ratios (average δ^{13}C $= -19.8$‰, δ^{15}N $= 8.8$‰) were generally within a C3 terrestrial range. One outlier (no. 370) had an elevated δ^{13}C value (δ^{13}C $= -17.2$‰, δ^{15}N $= 8.6$‰), which was more likely to be due to C4 consumption than due to marine fish consumption because of the lack of comparatively elevated δ^{15}N.

6.2.3 Northern European humans

A total of 19 sites reporting human isotopic results from Northern Europe were included in the meta-analysis. For details see Table A.16. There is only a single reported study from Northern Europe in the Roman period or Iron Age (Jørkov et al., 2010). Jørkov et al. (2010) analysed 70 individuals from 10 Roman Iron Age sites in eastern Denmark. Here, the results are recorded as

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[5] Results from (Hakenbeck et al., 2010) were kept as medians and ranges instead of means and standard deviations. The other sites included in this meta analysis were assumed to be normally distributed.

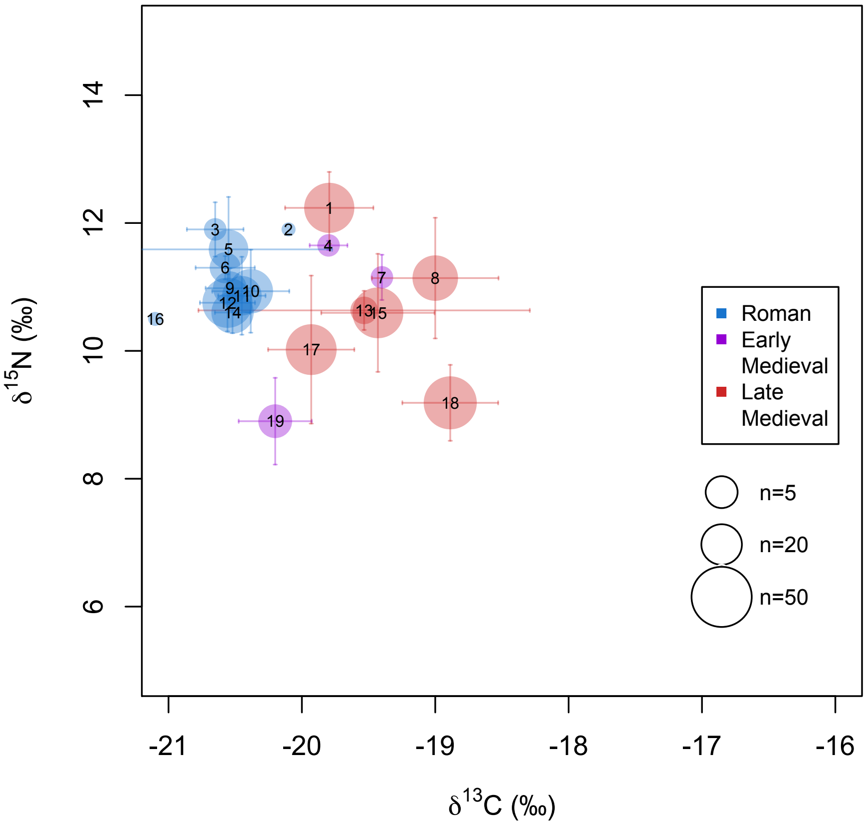

Figure 6.12: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for humans (adults) from previously published sites from Northern Europe. Point size is proportional to the square root of the number of individuals. Error bars show the 1σ range for each site. Sites are as follows: 1-Bernau, 2-Hoby, 3-Juellinge, 4-Tongeren, 5-Slusegard, 6-Himlingoje, 7-Antwerp, 8-Koksijde, 9-Anaes, 10-Bogebjerggard, 11-Varpelev, 12-Simonsborg, 13-Leuven, 14-Skovgarde, 15-Usedom, 16-Hagerup, 17-Tasdorf, 18-Giecz, 19-Namur*

ten separate sites. Note in Figure 6.12 how these results are extremely similar to one another, and extremely dissimilar to results from the rest of Northern Europe. The results showed that diet was remarkably uniform throughout the Roman Iron Age, and varied little according to factors like burial style, proximity to coast or sex of the individual. These 70 humans have the lowest average δ^{13}C values out of all the Northern European sites of (average -20.5 ± 0.2‰).

Reitsema et al. (2010) analysed humans and animals from the 11th- to 12th-century peasant population at Giecz, Poland, who had low δ^{15}N compared to other Northern European sites (average 9.2 ± 0.6‰). Late Medieval Namur, an inland site in Belgium, also had relatively low average δ^{15}N (average 8.9±0.7‰, n = 5; Ervynck et al., 1999). The other three sites from the same Belgian study had much higher human δ^{15}N, but no elevation in δ^{13}C to indicate a marine diet.

Schäuble (2005) studied three Late Medieval sites from Germany. The 20 adults from the urban site of Bernau, near Brandenburg had δ^{15}N values 2‰ higher than the 20 adults from the nearby village of Tasdorf, indicating that the consumption of high status foods like meat and fish was limited to urban areas. Interestingly, the coastal population at Usedom had similar results to the village of Tasdorf, suggesting that marine foods did not play a large role in the diet at this site, despite its proximity to the coast. The faunal values for all three sites were comparable, but the small numbers and large inter-site variation make any differences between sites difficult to assess. On this basis it appears that the difference between the urban site and the rural site is due to a genuine increase in the amount of high δ^{15}N foods, which could be due to meat in combination with fish (freshwater or marine) and omnivore meat. Of the five pigs sampled at these three sites, four have higher δ^{15}N values than the cattle or sheep/goat sampled from the same site.

6.2.4 Humans from England

A large number of previous isotopic studies have been conducted in England, which allows the country to be considered as a separate location. Many of the studies have provided a multi-period analysis of the same site (e.g. Jay and Richards, 2006; Lightfoot et al., 2009; Müldner and Richards, 2007a,b; Redfern et al., 2010; Richards et al., 1998). Two recent dissertations have provided a detailed analysis of diet in Roman Britain (Cummings, 2008)[6] and Anglo-Saxon England (Hull, 2008), incorporating evidence from historical and

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[6] The raw data from this thesis was not available and so not incorporated into the meta-analysis. The results are consistent with other Romano-British sites, however, as discussed in the text.

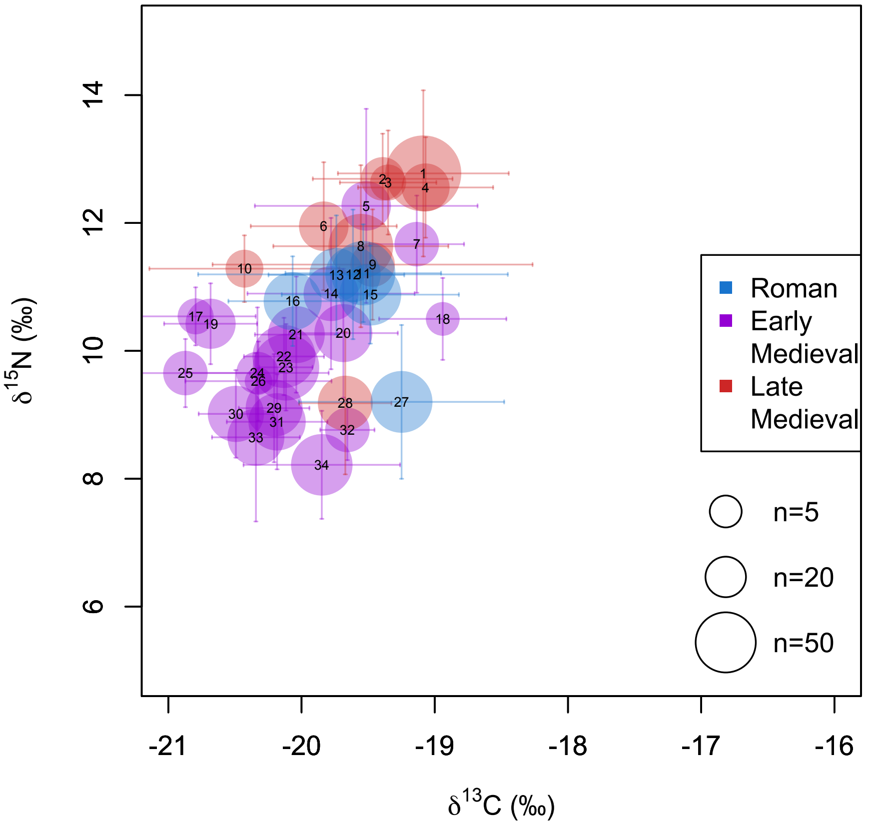

Figure 6.13: *Plot of δ^{13}C and δ^{15}N for humans (adults) from previously published sites from England. Point size is proportional to the square root of the number of individuals. Error bars show 1σ range for each site. Individual sites are as follows: 1-Fishergate, 2-Towton, 3-Whithorn (Priestly), 4-St Giles, 5-Caister-by-Yarmouth, 6-Warrington, 7-SouthAcre, 8-York, 9-Norwich, 10-Whithorn (Lay), 11-York, 12-6DT, 13-Gloucester, 14-BurghCastle, 15-3DT, 16-Catterick, 17-Spong Hill, 18-Norwich, 19-Morningthorpe, 20-Queenford, 21-York, 22-Westgarth, 23-Berinsfield, 24-Swaffham, 25-Bergh Apton, 26-Oxborough, 27-Poundbury, 28-Wharram Percy, 29-Winnall, 30-Alton, 31-Droxford, 32-Shavard, 33-Worthy Park, 34-Portway*

archaeological sources, as well as stable isotope analysis. The sites included in the meta-analysis are summarized in Table A.17 and Figure 6.13.

There is a large difference in δ^{15}N ratios between periods. Roman δ^{15}N is intermediate, averaging 10.7‰ for 263 individuals from 6 sites.[7] The majority of Romano-British studies found lower δ^{13}C and δ^{15}N than expected,

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[7] Tooth samples from Catterick (Chenery et al., 2011) were excluded, and only bone samples used.

suggesting a lower consumption of marine fish. This pattern was noted for the Romano-British sites studied by Cummings (2008), at Roman Gloucester (Chenery et al., 2010), and Catterick, North Yorkshire (Chenery et al., 2011). Cummings (2008) found that there was not evidence for the high levels of fish consumption mentioned by many Roman authors. Although many individuals and many of the sites she analysed had high overall δ^{15}N, which would be potentially indicative of marine protein in the diet, there was never a correspondingly significant elevation in δ^{13}C. She suggested that this could be the result of a combination of freshwater and marine fish in the diet, which together would elevate δ^{15}N while retaining a more terrestrial overall δ^{13}C. She concluded that it was unlikely that any individual had a diet consisting of more than 15% marine protein, and that for most individuals it was considerably lower.

At Roman Poundbury, there was less ambiguous evidence for fish consumption, with higher δ^{13}C associated with the more elite burial styles, suggesting that consumption of fish was limited by socio-economic factors (Richards et al., 1998). Two individuals with high δ^{13}C ratios (-15.8‰ and -16.3‰) were noted at an unusual Romano-British cemetery (Müldner et al., 2011). This cemetery contained several dozen individuals, all probably male, half of whom had been decapitated. The lack of correspondingly elevated δ^{15}N suggests that a large proportion of C4 plants were consumed by the two individuals with very high δ^{13}C.

Early Medieval English sites tend to have lower δ^{15}N, averaging 9.7 ± 1.3‰ for 499 individuals from 19 sites. Most of these individuals come from the investigation of Anglo-Saxon diet by Hull (2008), but also include Anglo-Saxon Berinsfield (Privat et al., 2002), post-Roman Queenford Farm (Fuller et al., 2006b), and the individuals of Early Medieval date from Norwich (Bayliss et al., 2004) and York (Müldner and Richards, 2007a). By comparison, Late Medieval English sites have much higher δ^{15}N ratios. The average δ^{15}N of 315 individuals from 9 sites is 12.1 ± 1.6‰. Many Late Medieval English sites showed isotopic evidence for large amounts of fish consumption, especially among the more elite and religious individuals. These sites include the 'priestly' burials from Late Medieval Whithorn (Müldner et al., 2009), and the 11th-century leper hospital in Norwich (Bayliss et al., 2004). This dietary change is usually attributed to the increase in marine fishing in the North Atlantic following AD 1000 (Barrett et al., 2004a), which may have been related to the importance of fish for medieval fasting practices among the devout.

The changes in English diet through time are demonstrated by a cross-section of results from York, spanning 1500 years (Müldner and Richards, 2007a) where individuals from the earliest and latest phases of their study have high δ^{13}C and δ^{15}N, indicative of marine fish consumption, with the Late Medieval phases having the highest isotopic ratios. They noted that the zooarchaeological record from York shows a shift from freshwater to marine species of fish in the later Medieval periods. They suggested that the supply networks and infrastructure supporting trade from the Humber estuary may have broken down in the post-Roman period. The most significant change to occur in the diet of York was between the High Medieval and Late Medieval periods (c.12th century) where there was a significant increase in δ^{15}N and δ^{13}C, indicating a shift to a diet with larger amounts of marine protein. However, the δ^{15}N ratios are higher than would be expected given the intermediate δ^{13}C ratios. Müldner and Richards (2007a) consider possible dietary factors that could contribute to a more terrestrial carbon signal while showing a high δ^{15}N, including freshwater fish and omnivore protein. The 155 individuals from the 13th- to 16th-century Gilbertine Priory at York were discussed in more detail by Müldner and Richards (2007b) who demonstrated that there was significant isotopic variation between individuals buried in different areas, most likely related to differences in marine fish consumption between men and women.

6.2.5 Overall trends in human isotopic ratios

The overall trends in human isotopic ratios were examined using a mixed multi-level model, similar in structure to that used to evaluate faunal trends. As before, Datecode (R, EM, LM), Location Code (Loccode = CE, Med, NE, UK), and Coastal/Inland are incorporated as explanatory variables, in addition to Sex (F, M, U). Inter-site variability is accounted for by keeping Site as a random effect. Only adults were included.

Table 6.9: *Statistics for mixed effects model fitted by REML for adult humans, calculated for all periods, all regions.*

Model 1: All periods, all locations
2696 Observations, 100 Groups. AIC= 4602 (δ^{13}C), 8082 (δ^{15}N) Random effect = ‘Site’
Fixed effects:

Date		δ^{13}C diff.	p	δ^{15}N diff.	p
Compared to EM	LM	0.49	< 0.0001	0.74	< 0.0001
	Roman	0.32	0.0003	0.51	0.003
Compared to Roman	LM	0.16	0.048	0.23	0.14
Location		δ^{13}C diff.	p	δ^{15}N diff.	p
Compared to Med	NE	-1.27	< 0.0001	0.87	0.01
	UK	-0.87	< 0.0001	0.91	0.002
	CE	-0.57	0.052	-0.02	0.97
Compared to CE	NE	-0.70	0.027	0.89	0.11
	UK	-0.29	0.31	0.93	0.07
Compared to NE	UK	0.41	0.044	0.04	0.91
Coastal/Inland		δ^{13}C diff.	p	δ^{15}N diff.	p
Compared to Coastal	Inland	-0.33	0.026	-0.67	0.01
Male/female		δ^{13}C diff.	p	δ^{15}N diff.	p
Compared to Female	Male	0.13	< 0.0001	0.32	< 0.0001

The initial output of the model (Table 6.9) compares all regions and all periods. The Mediterranean has significantly higher δ^{13}C compared to all other regions (for NE, effect size is 1.27‰, $p < 0.0001$, for England effect size is 0.87‰, $p < 0.0001$, for CE effect size is moderately significant at 0.57‰, $p = 0.052$). Mediterranean δ^{15}N also tends to be lower compared to Northern Europe (effect size 0.87‰, $p = 0.01$) and England (effect size 0.91‰, $p = 0.002$), but is similar to Central Europe ($p = 0.97$). Central Europe is distinct from other regions. Humans from Central Europe tend to have lower δ^{13}C compared to humans from the Mediterranean (effect size 0.56‰, $p = 0.052$), and higher

δ^{13}C compared to Northern Europe (effect size -0.70‰, $p = 0.027$). Central European humans also tend to have low δ^{15}N compared to England (effect size 0.89‰) and Northern Europe (effect size 0.93‰) although these differences are only moderately significant ($p = 0.07$ for England, $p = 0.11$ for Northern Europe). Northern European sites tend to have lower δ^{13}C compared to all other regions, and this effect is significant even for the UK-NE comparison (effect size 0.41‰, $p = 0.04$).

Overall, Roman individuals tend to have higher δ^{15}N and δ^{13}C compared to Early Medieval individuals (for δ^{13}C effect size = 0.32‰, $p = 0.0003$; for δ^{15}N effect size = 0.51‰ $p = 0.003$). Roman individuals tend to have slightly lower δ^{13}C ratios compared to Late Medieval individuals (effect size = 0.16‰, $p = 0.048$), but the difference in δ^{15}N is not significant($p = 0.14$). Late Medieval individuals have higher δ^{13}C (0.49‰$p < 0.0001$) and δ^{15}N (0.74‰$p < 0.0001$). Note that the size of the effect and its statistical significance is smaller for Roman compared to EM, than it is for LM compared to EM.This overall chronological effect may be reflecting what is largely an effect confined to England. If the four regions are modelled separately, only England retains a significant effect by period (see Table 6.10). The overall differences by sex for different location and periods are summarized in Figure 6.15.

There is a significant effect for Coastal/Inland differences for both δ^{13}C (effect size is -0.33‰, $p = 0.026$) and δ^{15}N (effect size is -0.67‰, $p = 0.01$). See Figure 6.14. Recall that such a significant Coastal/Inland effect was not observed among the faunal samples. If the statistics are calculated separately for each region, the Coastal/Inland effect remains similar for the Mediterranean, but is no longer significant for NE and England seaparetly (see Table 6.10). When results are separated by period (see Table 6.11) the Coastal/Inland effect is strongest for the Roman period alone.

In addition, small, but significant differences between sexes are affecting the overall model, with the effect size for Males being +0.13‰ for δ^{13}C ($p < 0.0001$) and +0.31‰ for δ^{15}N ($p < 0.0001$) (see Table 6.9). This relationship between

Table 6.10: *Statistics for mixed effects model fitted by REML for adult humans, calculated for each region separately.*

Model 2: Just Mediterranean, all periods
1109 Observations, 44 Groups. AIC= 1916 (δ^{13}C), 3605 (δ^{15}N). Random effect = Site

Date		δ^{13}C diff	p	δ^{15}N diff	p
Compared to EM	LM	0.65	< 0.0001	0.01	0.98
	Roman	-0.13	0.64	-0.14	0.78
Compared to Roman	LM	0.78	0.0034	0.14	0.76
Coastal/Inland					
Compared to Coastal	Inland	-0.58	0.02	-0.95	0.03
Male/female					
Compared to Female	Male	0.11	0.01	0.24	0.01

Model 3: Just Central Europe, all periods
346 Observations, 6 Groups. AIC= 541 (δ^{13}C), 855 (δ^{15}N). Random effect = Site

Date		δ^{13}C diff	p	δ^{15}N diff	p
Compared to EM	LM	0.19	0.59	-0.68	0.47
	Roman	0.45	0.28	0.07	0.94
Compared to Roman	LM	-0.63	0.23	0.75	0.53
Coastal/Inland					
Compared to Coastal	Inland	–	–	–	–
Male/female					
Compared to Female	Male	-0.03	0.67	0.12	0.22

Model 4: Just Northern Europe, all periods
178 Observations, 19 Groups. AIC= 210 (δ^{13}C), 426 (δ^{15}N). Random effect = Site

Date		δ^{13}C diff	p	δ^{15}N diff	p
Compared to EM	LM	0.34	0.27	0.33	0.67
	Roman	-0.82	0.02	0.87	0.29
Compared to Roman	LM	1.16	< 0.0001	-0.53	0.29
Coastal/Inland					
Compared to Coastal	Inland	-0.23	0.2	0.05	0.93
Male/female					
Compared to Female	Male	0.11	0.08	0.6	< 0.0001

Model 5: Just England, all periods
1063 Observations, 31 Groups. AIC= 1887 (δ^{13}C), 3080 (δ^{15}N). Random effect = Site

Date		δ^{13}C diff	p	δ^{15}N diff	p
Compared to EM	LM	0.37	0.0001	1.33	< 0.0001
	Roman	0.41	0.0001	0.87	< 0.0001
Compared to Roman	LM	-0.04	0.68	0.46	0.01
Coastal/Inland					
Compared to Coastal	Inland	-0.11	0.59	-0.66	0.18
Male/female					
Compared to Female	Male	0.21	< 0.0001	0.42	< 0.0001

Table 6.11: *Statistics for mixed effects model fitted by REML for adult humans, calculated for each period separately.*

Model 6: Just Roman, all regions
852 Observations, 28 Groups. AIC= 1349 (δ^{13}C), 2651 (δ^{15}N). Random effect = Site

Location		δ^{13}C difference	p	δ^{15}N difference	p
Compared to Med	NE	-1.4	< 0.0001	1.03	0.07
	UK	-0.28	0.19	0.75	0.22
	CE	0.09	0.84	-0.55	0.66
Compared to CE	NE	-1.49	0.0032	1.58	0.22
	UK	-0.37	0.42	1.3	0.31
Compared to NE	UK	1.12	0.0001	-0.28	0.67
Coastal/Inland					
Compared to Coastal	Inland	-0.46	0.01	-0.14	0.77
Male/female					
Compared to Female	Male	0.15	0.0037	0.3	0.0059

Model 7: Just Early Medieval, all regions
905 Observations, 33 Groups. AIC= 1236 (δ^{13}C), 2405 (δ^{15}N). Random effect = Site

Location		δ^{13}C difference	p	δ^{15}N difference	p
Compared to Med	NE	-0.56	0.12	1.48	0.07
	UK	-0.86	0.0003	0.7	0.16
	CE	-0.49	0.1	0.5	0.47
Compared to CE	NE	-0.08	0.84	0.98	0.26
	UK	-0.38	0.14	0.2	0.73
Compared to NE	UK	-0.3	0.36	-0.78	0.29
Coastal/Inland					
Compared to Coastal	Inland	-0.37	0.19	1.94	0.0059
Male/female					
Compared to Female	Male	0.04	0.24	0.13	0.0547

Model 8: Just Late Medieval, all regions
939 Observations, 44 Groups. AIC= 1911 (δ^{13}C), 2960 (δ^{15}N). Random effect = Site

Location		δ^{13}C difference	p	δ^{15}N difference	p
Compared to Med	NE	-0.93	0.01	0.47	0.39
	UK	1.04	0.0016	1.59	0.0016
	CE	-1.28	0.11	-1.19	0.33
Compared to CE	NE	0.35	0.67	1.66	0.19
	UK	0.24	0.77	2.79	0.03
Compared to NE	UK	-0.11	0.78	1.12	0.08
Coastal/Inland					
Compared to Coastal	Inland	-0.39	0.13	-0.58	0.14
Male/female					
Compared to Female	Male	0.2	< 0.0001	0.51	< 0.0001

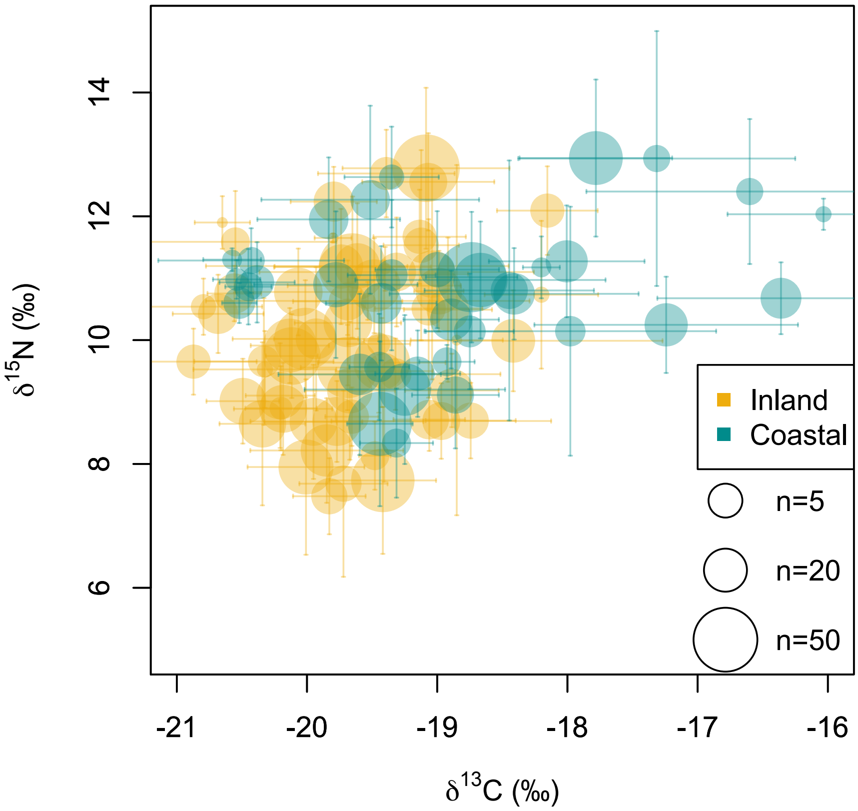

Figure 6.14: *Plot of $\delta^{13}C$ and $\delta^{15}N$ for humans (adults) from previously published sites showing Coastal/Inland differences. Point size is proportional to the square root of the number of individuals.*

δ^{13}C and δ^{15}N is similar to what would be expected for a trophic level effect (see Chapter 3). This effect is also consistent for each region independently, but only significant for those regions (Med and UK) represented by the largest number of individuals (see Table 6.10). The effect for sex is largest in the Late Medieval period, smaller in the Roman period, and not significant in the Early Medieval period, suggesting that sex-based dietary differences may have changed through time (see Table 6.11 and Figure 6.15).

In Chapter 5, excluding the princely burials from Naples and Florence (Fornaciari, 2008) made a significant difference to the model. Due to the larger number of studies here, the inclusion or exclusion of these sites makes no significant difference. In Chapter 5 it was also noted that juveniles tended to have slightly lower isotopic ratios compared to adults. When the model above

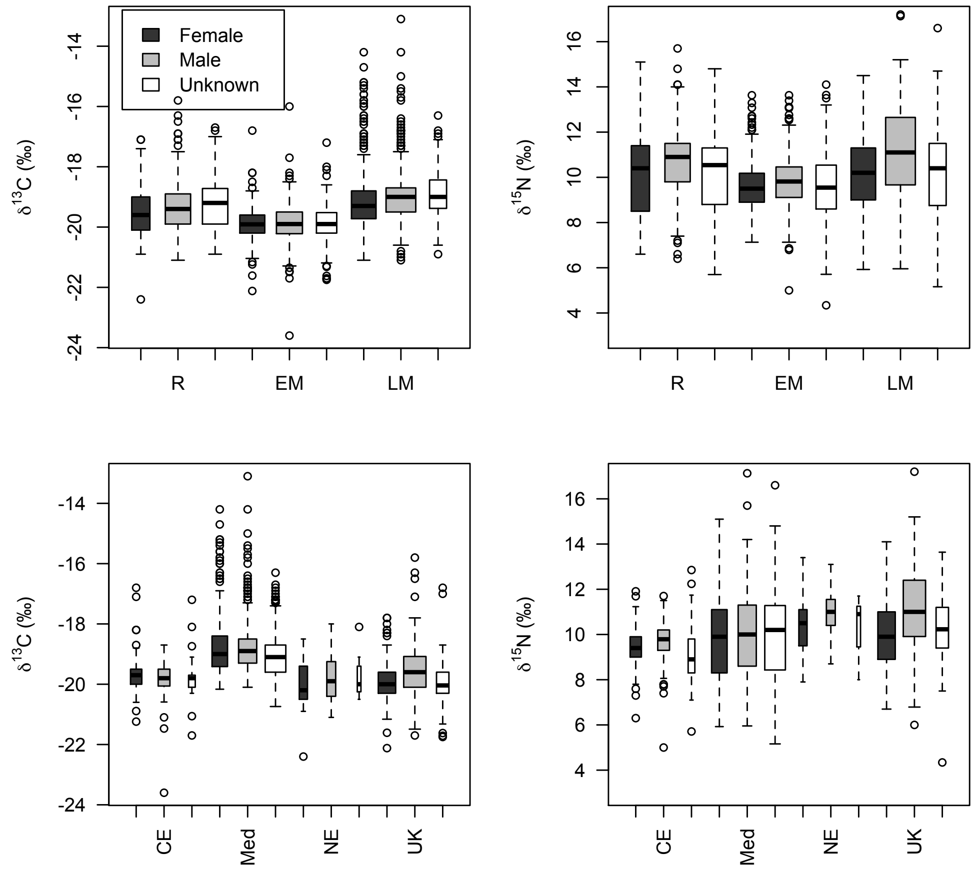

Figure 6.15: *Box plot summaries of $\delta^{13}C$ and $\delta^{15}N$ for human from meta-analysis, by sex, period and location. Box width is proportional to the square root of the number of individuals.*

is re-run with adults and juveniles (subadults that are old enough not to be influenced by a weaning signal), and including Age Category (A/J) as an explanatory variable, there are no significant differences for Juveniles. The effect size for δ^{13}C is 0.04‰, $p = 0.61$. The effect size for δ^{15}N is 0.05‰, $p = 0.58$.

Humans from the Mediterranean tend to have higher δ^{13}C, while the δ^{15}N ratios in humans tend to be higher in England and Northern Europe tend to be higher. There was a similar pattern for faunal results as well, although the effect size was smaller and the differences were only significant for the much higher δ^{13}C in the Mediterranean. There are many potential explanations for the inter-regional differences in human isotopic ratios. Since the human and animal isotopic ratios appear to track one another, the effect may be partly

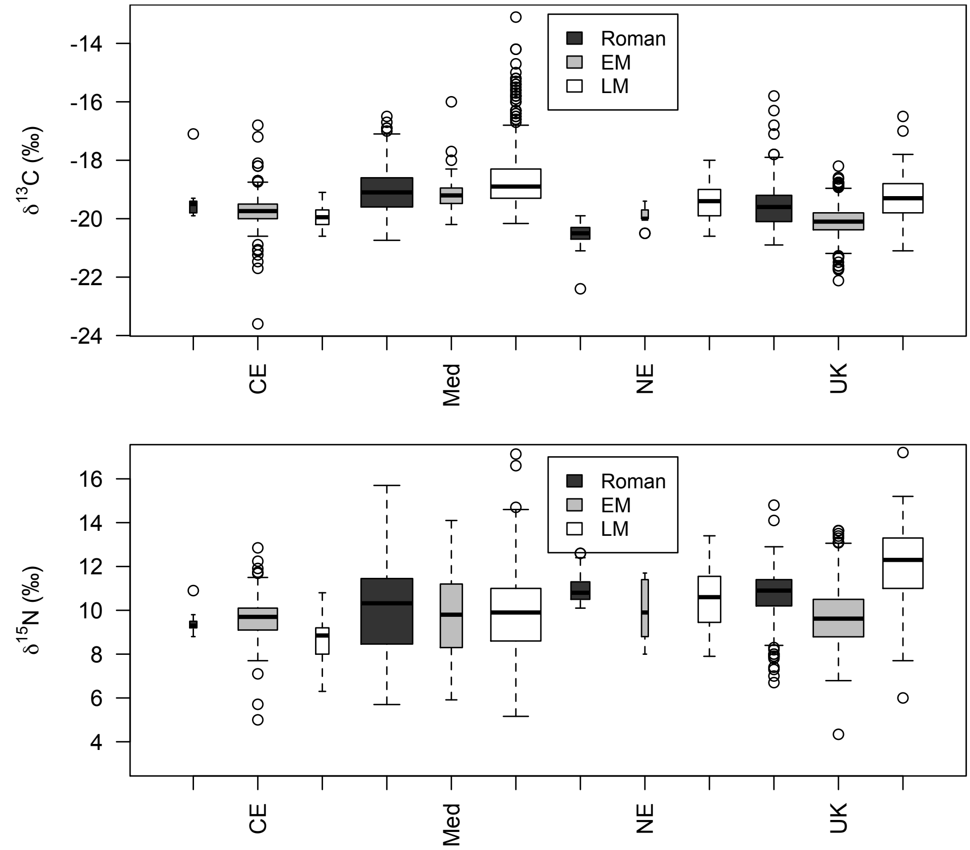

Figure 6.16: *Box plot summaries of $\delta^{13}C$ and $\delta^{15}N$ for human from meta-analysis, period and location. Box width is proportional to the square root of the number of individuals.*

due to effects at the base of the food chain. These could be purely geographic or climatic differences, relating to temperature, precipitation or forest cover (see Chapter 3). Anthropogenic effects, such as different agricultural practices, could also be responsible for such differences at the base of the foodchain. For example, different manuring strategies may affect δ^{15}N and the adoption of C4 plants as animal fodder could affect δ^{13}C in both humans and animals, has has been argued for Islamic Spain (Mundee, 2010). The same possible factors may also explain the significantly lower δ^{13}C and δ^{15}N in the Early Medieval period across all regions, which is also mirrored in the faunal variation (see Figure 6.16).

Some of the inter-regional human variation in isotopic ratios may be inde-

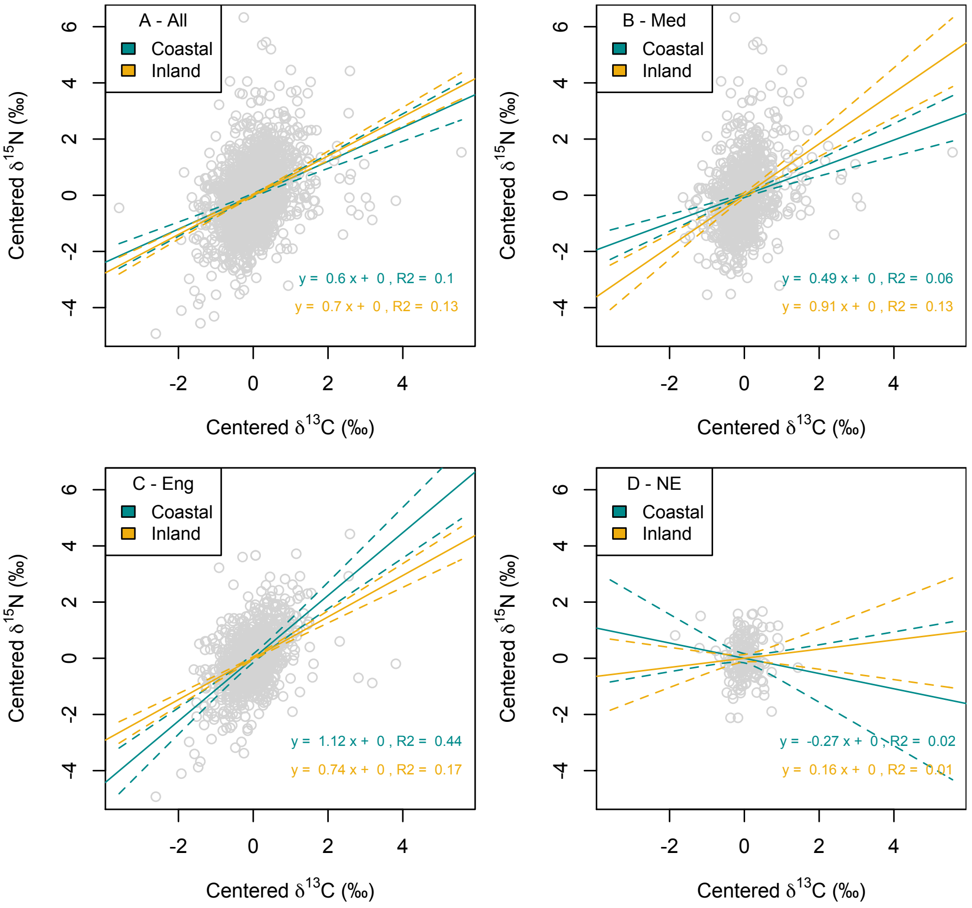

Figure 6.17: *Comparison of regression relationship between $\delta^{13}C$ and $\delta^{15}N$ for coastal and inland sites from different regions: A - All data, B - Mediterranean, C - England, D - Northern Europe. (Central Europe was not included because it included no coastal sites. The original datapoints, centred around the mean of each site, are plotted. Dashed line shows the 95% confidence interval for the regression relationship. The regression equation, including R^2 is also shown. Note that none of these regression relationships are very strong ($R^2 < 0.5$) and that the slope of the line is strongly influenced by outliers. These two factors result in an apparently poor fit of the two regression lines when they are visually compared to the overall trends in the data.*

pendent of inter-regional faunal changes. The model clearly showed an effect in humans for Coastal/Inland differences, where none was apparent in the fauna. In addition to the isotopic baseline being higher in δ^{13}C in the Mediterranean, humans from the Mediterranean may have also consumed higher proportion of high δ^{13}C foods compared to humans in other regions.

Recall from Chapter 5, that there were significant correlations for human δ^{13}C and δ^{15}N at several Italian sites. Since marine foods are usually higher in both δ^{13}C and δ^{15}N, it is often expected that a population consuming variable amounts of marine protein will show a strong correlation between δ^{13}C and δ^{15}N (Richards and Hedges, 1999). Populations consuming variable quantities of animal protein may also be expected to show a positive relationship between δ^{13}C and δ^{15}N with a slope closer to 3–5, reflecting the relative trophic level increase in δ^{15}N versus δ^{13}C. To test whether this effect could be observed in the meta-analysis dataset as a whole, I first centred the δ^{13}C and δ^{15}N ratios according to the mean of each site. The variation (or scale) of the data was left unchanged. This removes the effect of site-level variation, allowing data from different sites to be grouped together without biasing the results. Then regression statistics were calculated for different groups of data, comparing regression from coastal sites to that from inland sites.

From Figure 6.17 it is clear that δ^{13}C and δ^{15}N are not normally strongly correlated on a regional level. The strongest correlation $R^2 = 0.44$ is for coastal sites from England, which has a slope of about 1.1. Inland sites from England show are less strongly correlated ($R^2 = 0.17$) but have a lower slope (0.74). Similarly, few meaningful patterns emerge when assessing correlation in different periods (see Figure 6.18). The strongest correlations are from Early Medieval coastal sites ($R^2 = 0.43$) and Late Medieval inland sites ($R^2 = 0.26$), which have relatively similar slopes (1.2 and 1.05). At the level of the meta-analysis it seems that a variety of other factors (both dietary and environmental) affect isotopic ratios, and that therefore isotopic ratios do not reflect a strong correltion between δ^{13}C and δ^{15}N. It is possible that some of this variability is masked in data from England, which contains a relatively large amount of samples from a relatively small geographical area, and where correlation between δ^{13}C and δ^{15}N is most significant.

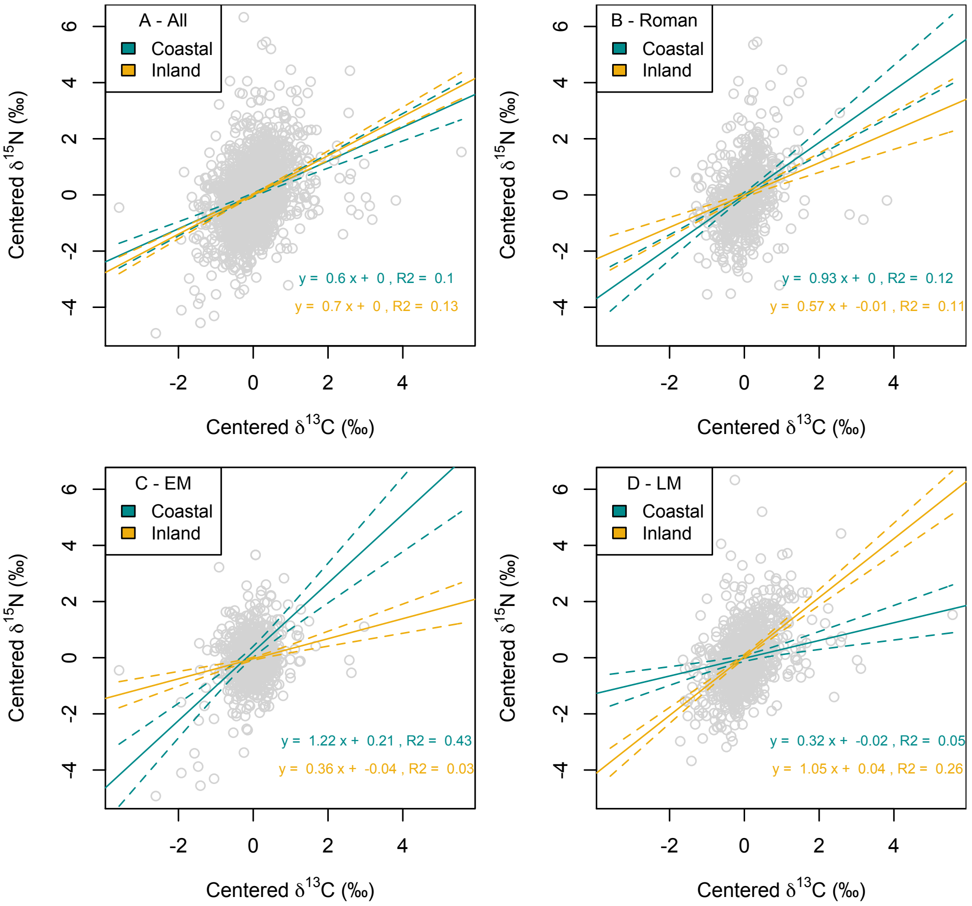

Figure 6.18: *Comparison of regression relationship between $\delta^{13}C$ and $\delta^{15}N$ for coastal and inland sites from different regions: A - All data, B - Mediterranean, C - England, D - Northern Europe. (Central Europe was not included because it included no coastal sites. The original datapoints, centred around the mean of each site, are plotted. Dashed line shows the 95% confidence interval for the regression relationship. The regression equation, including R^2 is also shown. Note that none of these regression relationships are very strong ($R^2 < 0.5$) and that the slope of the line is strongly influenced by outliers. These two factors result in an apparently poor fit of the two regression lines when they are visually compared to the overall trends in the data.*

6.3 Intra-site human–faunal isotopic differences

Intra site comparisons of human-faunal isotopic ratios were made for 19 of the sites in the meta-analysis, The faunal baseline was calculated based on the average isotopic ratios for cattle, sheep/goat and pigs from each site. This method is not entirely satisfactory, since different species would have contributed to the diet in different proportions, and the fauna analysed from each site may not be representative of the isotopic ratios of the fauna actually eaten. For some sites, very few faunal specimens were available, and so the averages were based on very small sample sizes. Comparisons were only made between sites where the number of individuals (both fauna or human) was greater than three. Fauna from one site were not used to represent multiple nearby sites, but it would be possible to extend this method to make such comparisons infuture. Given these uncertainties and assumptions, and the relatively small number of sites including both animal and human isotopic ratios, the interpretive power of these intra-site human–faunal relationships is extremely limited. Nevertheless, here it is used to provide a link between the human and faunal geographic and chronological patterns discussed above.

In general, sites with higher Δ^{15}N human-faunal relationships also have higher Δ^{13}C human-faunal relationships (see Table 6.12 and Figure 6.19) but there is considerable variation. At most sites, the human-faunal differences are equal to or greater than the differences that would be expected for a single trophic level increase of about 1‰ for δ^{13}C and $3 - 5$‰ for δ^{15}N (see Chapter 3). This suggests that the measured fauna to not completely reflect the isotopic range of plants and animals consumed by humans, and/or that trophic level estimates derived from measurements of other species are not directly applicable to human diets. One obvious complicating factor is the consumption of fish (marine and freshwater) increasing human δ^{13}C and δ^{15}N relative to local fauna.

Table 6.12: *Summary of intra-site human-faunal comparisons for $\Delta^{13}C$ and $\Delta^{15}N$. The upper and lower limits of the 95% confidence range for the difference of both $\Delta^{13}C$ and $\Delta^{15}N$ was calculated using a t-test and is also shown.*

Site	Date	Region	Δ^{13}C			Δ^{15}N			
			lower	upper	mean diff	lower	upper	mean diff	CI
Klettham	R	CE	1.54	2.8	2.17	0.71	2.06	1.38	I
Isola Sacra	R	Med	1.32	2.32	1.82	4.74	6.9	5.82	C
Velia	R	Med	0.75	2.4	1.57	2.59	5.84	4.21	C
Leptiminus	R	Med	0.54	2.6	1.57	0.91	6.51	3.71	C
Gloucester	R	UK	1.5	2.16	1.83	4.22	5.69	4.96	I
Catterick	R	UK	1.24	1.67	1.45	3.75	5.28	4.52	I
Volders	EM	CE	1.58	2.06	1.82	3.69	5.06	4.38	I
Berinsfield	EM	UK	1.01	1.56	1.28	3.49	4.23	3.86	I
Grenoble	LM	CE	0.61	1.4	1.01	3.1	4.77	3.93	I
Albarracin	LM	Med	0.69	1.22	0.96	2.44	5.83	4.14	I
Ibiza	LM	Med	0.93	1.64	1.28	3.83	5.27	4.55	C
Kastella	LM	Med	0.91	2.04	1.47	3.12	4.86	3.99	C
Gandia	LM	Med	1.35	3.37	2.36	4.51	6.5	5.51	C
Bernau	LM	NE	0.79	2.42	1.61	4.74	5.7	5.22	I
Tasdorf	LM	NE	-0.03	2.82	1.39	1.55	4.24	2.89	I
Koksijde	LM	NE	1.3	3.3	2.3	4.26	7.31	5.79	C
St Giles	LM	UK	2.21	2.96	2.59	5.97	7.42	6.69	I
WP	LM	UK	1.7	2.21	1.96	2.49	4.17	3.33	I
York	LM	UK	1.92	2.21	2.07	4.2	5.01	4.61	I

All values ‰

When Δ^{13}C and Δ^{15}N ratios are compared for inland and coastal sites, however, there are no apparent differents (possibly confounded by the small number of sites included, see Figure 6.20). The mean Δ^{13}C for the 7 coastal sites (1.78‰) is very similar to the mean Δ^{13}C of the 12 inland sites (1.68‰, based on taking the average of the averaged site-based difference). The Δ^{15}C relationship for coastal sites is slightly higher on average compared to inland sites (4.80‰ vs. 4.16‰) but given the uncertainty this difference is not necessarily meaningful, and is skewed by the very low Δ^{15}N between humans and fauna at Klettham.

Figure 6.21 shows that there is a wide variation in Δ^{13}C and Δ^{15}N for sites within different regions, but there does not to be any systematic difference be-

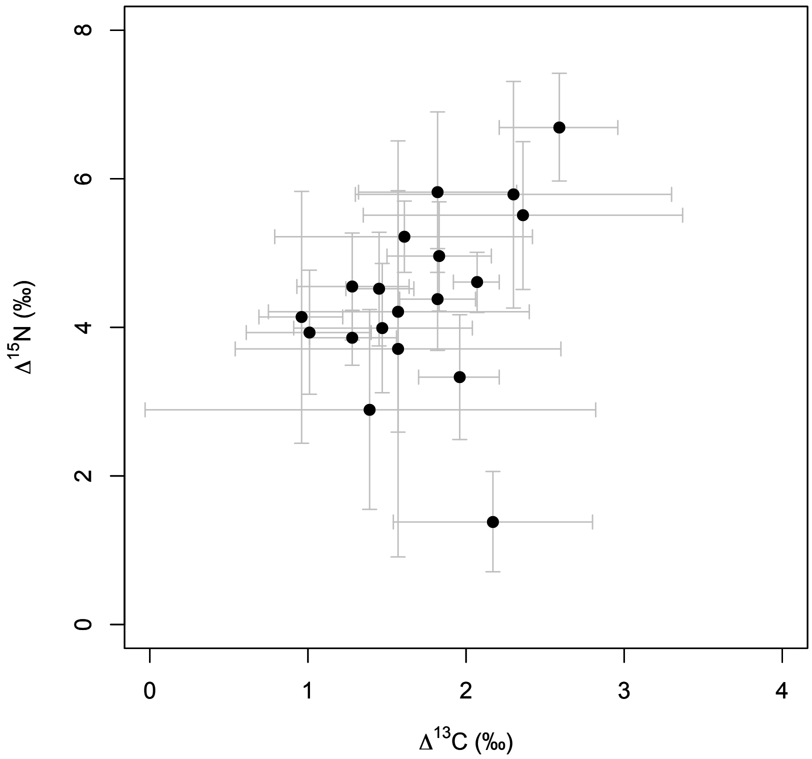

Figure 6.19: *Plot of human–faunal* $\Delta^{13}C$ *vs.* $\Delta^{15}N$ *for inland and coastal sites. Error bars show the* 95% *confidence range of the estimated difference between human and faunal isotope ratios at each site.*

tween regions. This is consistent with the result of the meta-analysis conducted separately for humans and animals, which suggests that inter-regional variation is is consistent between humand and fauna (noting especially the higher δ^{13}C found in both humans and fauna from the Mediterranean).

There is a similar range in Δ^{13}C and Δ^{15}N when sites are compared chronologically, and interpretations of these patterns are limited by the fact that human-faunal relationships were only reconstructed for two EM sites. It should be noted, however, that humans seem to have especially high δ^{15}N relative to fauna for the Roman and Late Medieval sites. It was observed above that humans from the EM period tend to have lower δ^{15}N, but no change through time was observed in the fauna. This comparison of intra-site Δ^{15}N is consistent with

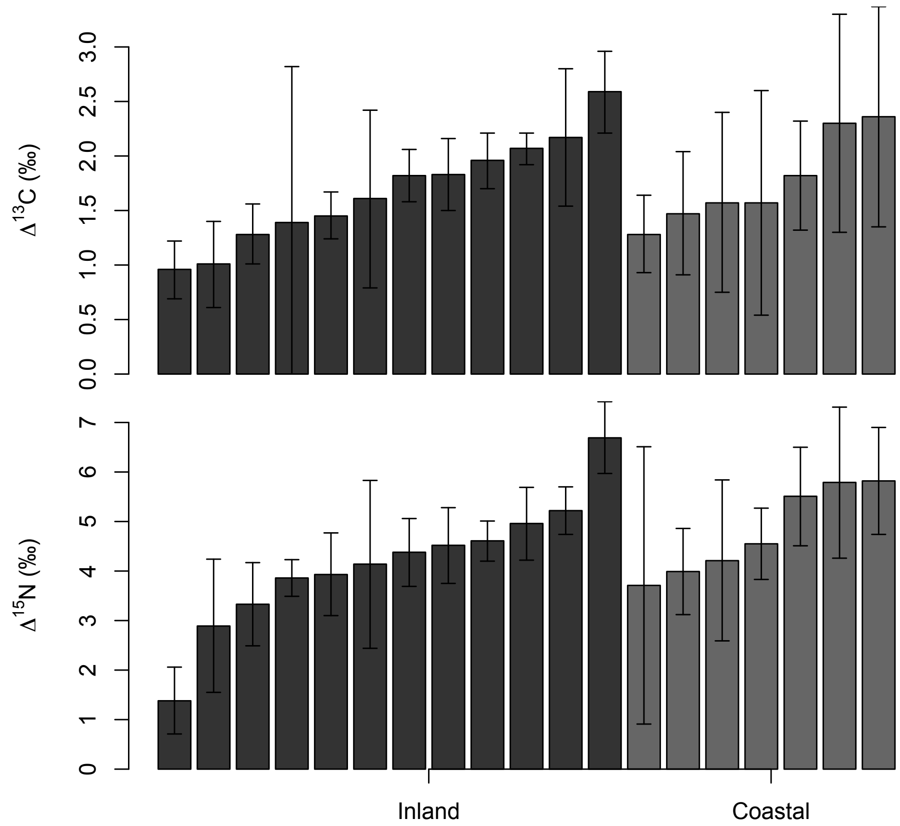

Figure 6.20: *Plot of human–faunal $\Delta^{13}C$ and $\Delta^{15}N$ for inland and coastal sites. Error bars show the 95% confidence range of the estimated difference between human and faunal isotope ratios at each site.*

the above evidence, and suggests that the chronological effect for humans may be partly independent from an underlying variation in faunal isotopic ratios.

6.4 Summary of results from meta-analysis

- Fauna from the Mediterranean can be distinguished from other regions because of their significantly higher δ^{13}C, which is consistent across all periods and species. Some Late Medieval Spanish sites have especially high faunal δ^{13}C.

- There are no significant differences in fauna for coastal vs. inland sites.

- Cattle and sheep/goat have similar isotopic ratios, but pigs tend to have

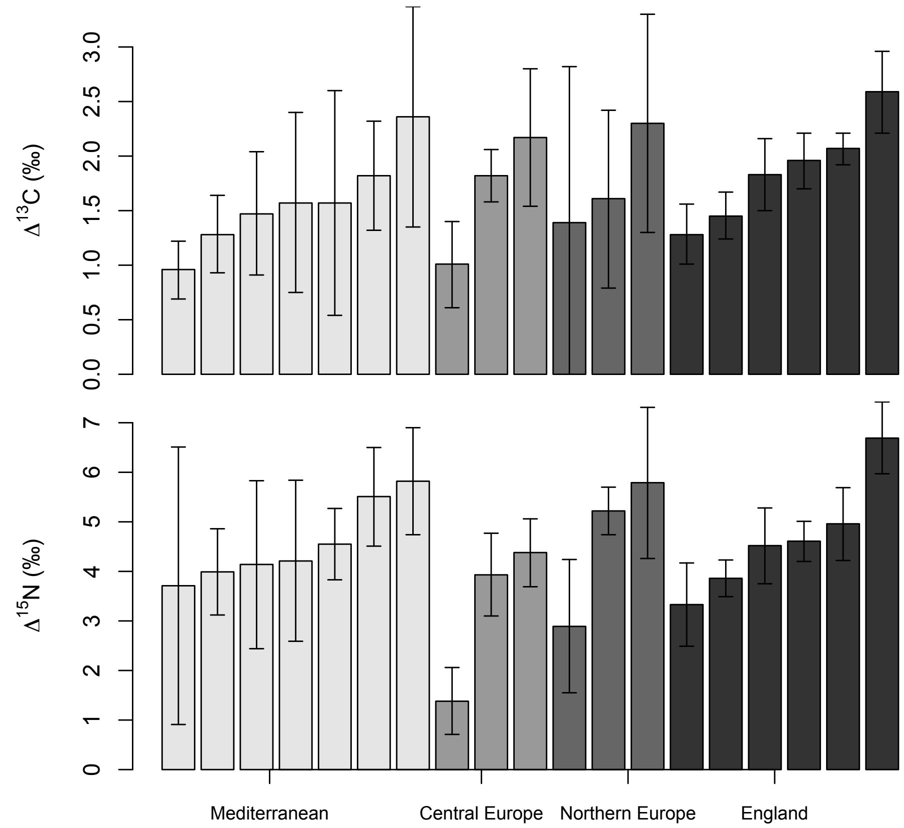

Figure 6.21: *Plot of human–faunal $\Delta^{13}C$ and $\Delta^{15}N$ by location*

significantly higher δ^{15}N and somewhat significantly higher δ^{13}C. This is consistent for all regions.

- Early Medieval fauna may have lower δ^{15}N compared Roman fauna, but the effect is only significant in the comparison where inter-regional differences have been simplified (effect size is 0.77‰, $p = 0.047$). The simplified comparison also shows that LM fauna have moderately significantly higher δ^{13}C compared to Roman fauna (0.25‰$p = 0.051$.

- Humans from coastal sites tend to have significantly higher δ^{13}C (effect size 0.33‰, $p = 0.026$) and δ^{15}N (0.67‰, $p = 0.01$) compared to inland sites.

- Males tend to have slightly but significantly higher isotopic ratios com-

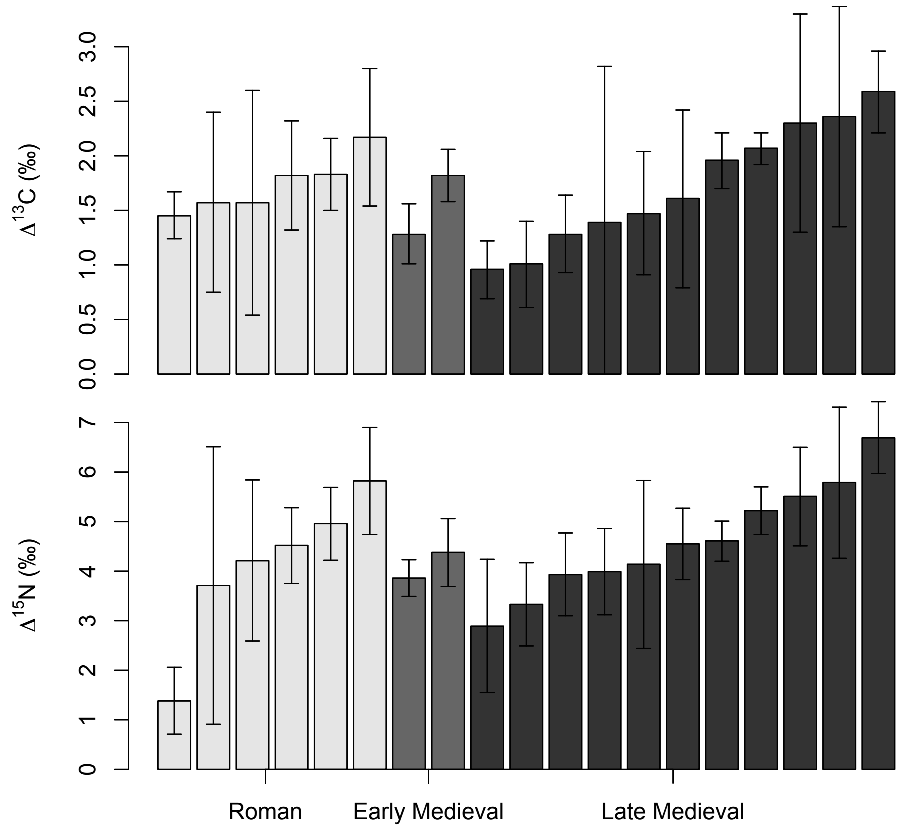

Figure 6.22: *Plot of faunal-human $\Delta^{13}C$ and $\Delta^{15}N$ by period*

pared to females +0.13‰ for δ^{13}C ($p < 0.0001$) and +0.32‰ for δ^{15}N ($p < 0.0001$). This effect is largest for the Late Medieval period, and smallest for the Early Medieval period.

- When juveniles were added to the meta-analysis, they were not significantly different from adults. Infants were excluded, but recall that the infants analysed from Italy in Chapter 5 had significantly higher δ^{13}C and δ^{15}N compared to adults.

- Early Medieval humans have slightly but significantly lower δ^{13}C and δ^{15}N compared to the Roman and Late Medieval periods. For δ^{13}C the effect size is 0.32‰ for EM-R ($p = 0.0003$) and 0.49‰ for EM-LM ($p < 0.0001$). For δ^{15}N the effect size is 0.51‰ for EM-R ($p = 0.003$) and 0.74‰ for

EM-LM ($p < 0.0001$). This effect is most significant for England, and less significant for other regions.

- Comparison of intra-site Δ^{13}C and Δ^{15}N for 19 of the sites included in the meta-analysis shows that humans have isotopic ratio increases relative to fauna equal to or greater than what would be expected from a single trophic level shift. This suggests fauna isotopic ratios do not adequatly represent the isotopic variability of the human diet, and that trophic level effects may be underestimated for humans. This problem is illustrated by the fact that humans from coastal sites did not have different Δ^{13}C and Δ^{15}N relationships compared to inland sites, even though the meta-analysis of humans and fauna separately showed that there were significant differences between coastal and inland sites for humans, but not for fauna.

In science the individual fact is of importance only so far as it demonstrates a general law. The law is the end, and the fact is the means to it [...] In history, the opposite is true.
—R. Collingwood, 1922, *The Philosophy of History*

7

Discussion: Towards a Consilience of Isotopic and Archaeo-Historical Evidence

Europe underwent significant social, political and economic changes from the height of the Roman empire in the 1st century AD to the beginning of the Renaissance in the 15th century. This thesis sought to address how these changes might have affected food practices. In Chapter 2, I presented the historical and archaeological evidence for a variety of factors that could have influenced diet. Combined, these factors suggest that Early Medieval diet was substantially different from Roman diet. Based on this hypothesis, the main question this study sought to answer was: in the early Medieval period, did the average person consume more meat than in the Roman period? Why or why not (and to what extent could stable isotope ratios be used to answer such a question)? Addressing this question requires a closer examination of the factors that may have affected dietary practices in Roman and Medieval Europe. In Chapter 1.3 I listed ten ways in which diet could have been influenced by historical and cultural forces during the period in question. I re-phrase them below:

- How integrated was the Roman economy, and to what extent was the population dependent on imported food?
- How does this picture of Roman economic integration differ for inland, rural areas?
- Did Romans have a different food ideology compared to non-Roman European populations?
- Did Christianity influence dietary choices?
- In the Early Medieval economic depression, were inland/rural areas especially marginalized?
- Were food practices in urban areas affected by the Early Medieval economic depression?
- What role did climate and environmental change play, and how does this relate to changing agricultural practices?
- Did the revival of urbanization throughout Europe c. AD 1000 change food practices?
- What was the impact of new foods as a result of increasing trade in the Late Medieval period?
- Throughout all periods, how did an individual's status affect dietary choices?

As described in Chapter 3, stable isotope analysis is useful tool for addressing many of these questions, since it enables a direct and quantifiably comparable estimate of different dietary categories. In section 1.3 I explained how the questions listed above generate hypotheses that are testable using stable isotope analysis. These testable hypotheses formed the basis of the design of this study, as described in Chapter 4. I combined new analyses from Italian sites (Chapter 5), with a meta-analysis of previously published European data (Chapter 6) to examine isotopic differences in humans and fauna between the

Roman and Medieval periods. In this chapter, I discuss how the data presented in Chapters 5 and 6 can be used to answer some of the ten questions outlined above. I have grouped these questions into four topics: 1) Roman Diet and Economy, 2) Early Medieval Diet Change, and 3) Late Medieval Dietary Trends, and 4) Diet and Social Status AD 1–1500.

7.1 Roman Diet and Economy

In order to describe and explain the Roman–Medieval dietary transition, it is necessary to investigate Roman diet more precisely. The hypothesis of diet change at the start of the medieval period rests on the assumption that the Roman diet and economy were particularly grain-based. Estimating the animal fraction of the Roman diet would enable us to determine whether this grain-based impression of the Roman empire is true. However, the previous studies of Roman diet (Craig et al., 2009; Prowse et al., 2004) suggested there may be a problem with isotopic analysis in Roman Italy: that human δ^{15}N was anomalously high, and could not necessarily be explained by a marine contribution using standard isotopic models. One of the aims of this research was to better understand the problem of fish consumption and isotopic models in Roman Italy. It is essential if we are to estimate the animal protein fraction of the diet and make comparisons with later Medieval developments, since the animal protein fraction is partly dependent on the amount of fish estimated to have been consumed. Examining fish consumption in the Roman world is also important because the consumption of marine fish in inland areas can be used to infer levels of economic integration and quality of transport infrastructure.

Because of the isotopic discrimination for carbon in marine systems, and because of the complexity of trophic level relationships in marine environments, marine fish tend to be significantly higher in both δ^{13}C and δ^{15}N compared to terrestrial foods (see Chapter 3). Stable isotope analysis has been very successful at identifying fish consumption in Mesolithic Europe where high

δ^{13}C (up to $-12‰$) and high δ^{15}N (up to 17‰) have been found in humans (e.g. Richards and Hedges, 1999). Using the isotopic ratios of modern humans known to consume heavily marine diets as endpoints and assuming a linear relationship between these endpoints, it is possible to estimate the fraction of marine protein in the diet in these populations, which frequently suggests levels of marine protein consumption greater than 50%, and in some cases up to 90% (Richards and Hedges, 1999).

Historical and archaeological information suggests that fishing was important in the Roman world, both economically and socially (Chapter 2). Economically, it was an important source of protein for the poor, and the exploitation of Mediterranean fish stocks took the pressure off land, which could be used to produce the calories to feed the growing Roman population through grain more easily than it could through the raising of livestock. That the consumption of fish played an important cultural role is demonstrated by the elite's conspicuous preference for select species, and by the huge demand for the fish sauce *garum*, which was imported across the Empire. It is tempting to expect that Roman levels of fish consumption, as revealed through stable isotope ratios, would be significant (perhaps greater than 25%), though likely lower than Mesolithic North Atlantic levels.[1].

Instead, the review of previous Italian studies presented in Chapter 4, the new data presented in Chapter 5, and the meta-analysis of all available Roman data in Chapter 6 show that the isotopic evidence for Roman marine fish consumption is limited and that Roman fish consumption was probably significantly less than expected. The consistent pattern that emerges from the Roman stable isotope data is one where humans have relatively high δ^{15}N compared to local fauna, while maintaining relatively terrestrial δ^{13}C. Figure 7.1 illustrates

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[1] A diet containing 25% protein from fish is comparable with the average of all developed nations in Asia. Modern Mediterranean countries tend to consume around $10-12\%$ of their total protein intake as fish, although the Italian national average is only 6%. This is based on 2003 national food balance data from the FAO, available at http://www.fao.org/fishery/statistics/global-consumption/en

the difference between the Italian results and a typical Mesolithic sites Téviec and Höedic (Richards, 1998). The regression line for the nine Mesolithic adults has a slope of 1.4, while the slope for the coastal Italian Romans is 2, and the slope for the inland Italian Romans is 2.5.[2] The 95% confidence regions for the Italian coastal sites and the Italian inland sites overlap. The relatively high slope for Italy requires explanation. If it is assumed to be the result of variability in marine fish consumption, it would be expected to align with the δ^{13}C and δ^{15}N endpoint of a 100% marine fish diet. However, as can be seen from Figure 7.1, the slope of this relationship in Italy is too high. Extending the relationship to a δ^{13}C ratio of -12‰ (consistent with marine fish ratios from the Mediterranean as discussed in Chapter 6), the corresponding δ^{15}N ratio would be > 20‰, far exceeding plausible human isotopic ratios based on fish consumption.

Craig et al. (2006) suggest that northern Europeans and Mediterraneans may not be directly comparable in isotopic estimates of fish consumption. If Mediterranean fish had lower δ^{13}C compared to the Atlantic and North Sea it would change the 100% marine diet endpoint and lead to an underestimation of the amount of fish consumed in the Mediterranean compared to northern Europe. However, the more recent analysis of archaeological Mediterranean fish samples discussed in 6.1.6 have δ^{13}C comparable with northern Europe (-14 to -12‰), which suggests that this explanation may not be true. Instead it was observed that Mediterranean fish δ^{15}N ratios are $2 - 3$‰ lower than other regions. At the same time, δ^{15}N ratios from Italy are relatively high. In the following discussion, I consider the effects of factors that may affect human δ^{15}N, such as manuring, animal protein consumption and fish consumption assuming a typically used estimate for δ^{15}N a human consuming a 100% marine diet of 18‰. I then consider whether dietary reconstructions can be improved

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[2] Note that unlike the regression analysis in Chapter 5, results were not centred for each individual site. Rather, all Italian coastal individuals were treated as a single site, as were all Italian inland individuals.

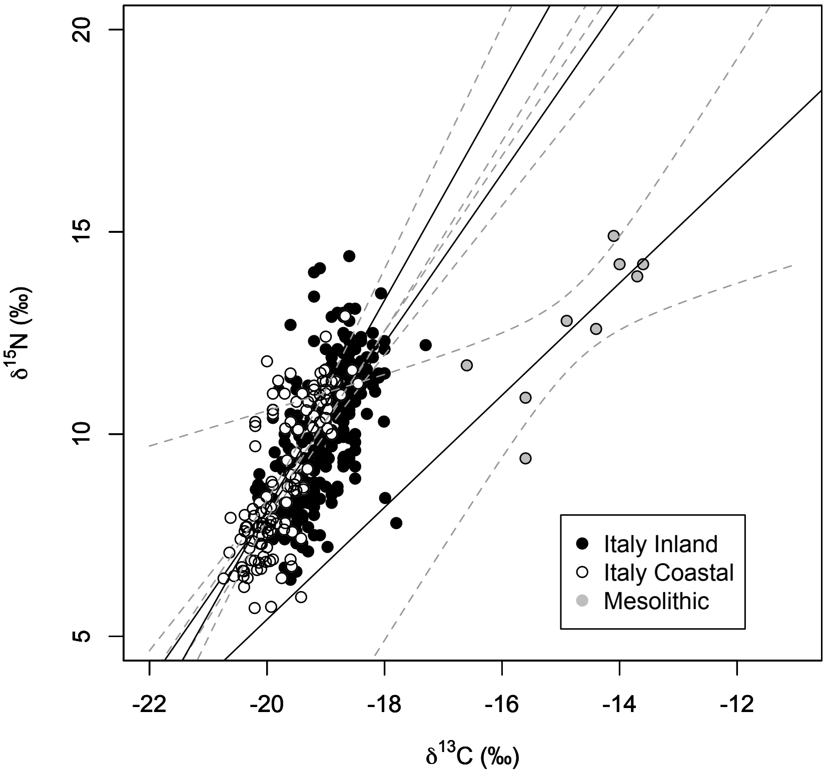

Figure 7.1: *Isotopic results from Roman Italy compared to Mesolithic Téviec and Höedic (Richards, 1998). Regression lines for each of the three populations are also plotted. Dashed line shows the* 95% *confidence interval for each regression line.*

further by using a more realistic δ^{15}N estimate of 12‰, and by accounting for the effect of the incorporation of non-protein carbon to collagen.

7.1.1 An isotopic model for Roman diet

We must determine whether the isotopic ratios of Romans from Italy are compatible with realistic diets using standard isotopic models, or whether additional factors, such as differences in carbon routing, need to be considered. In order to do so, I examine the available isotopic evidence, drawing on comparisons between coastal and newly-analysed inland sites using several different isotopic models.

In Chapter 5 I observed that coastal Italian sites have significantly higher δ^{13}C compared to inland Italian sites, with an effect size of 0.57‰ ($p = 0.04$), taking into account random inter-site variation, Date, and Sex of the individuals. There were no significant differences for coastal or inland sites based on δ^{15}N. There was a wide range in δ^{15}N among humans, with some very low ratios (around 6‰), and some very high ratios (around 13‰). The overall range in δ^{15}N for Roman Italy was 5.7 – 14.4‰. The low δ^{15}N and terrestrial δ^{13}C of some individuals from the inland Roman populations of Casale del Dolce and Osteria della Fontana presented in Chapter 5 suggests the importance of low δ^{15}N protein sources (grain and/or legumes) in the diet of Roman rural populations. At the same time, there are individuals with significantly higher δ^{15}N and slightly higher δ^{13}C at both of these sites, suggesting that some individuals had diets consistently higher in animal meat and fish. Similar intra-site groups were previously noted at Velia (Craig et al., 2009) and ANAS (Prowse et al., 2004). These groupings may be the result of movement either of high δ^{15}N foodstuffs (meat and fish) available only to a subset of the population, or to the movement of people from areas where these goods were more commonly consumed. The isotopic ratios of collagen represent an average of the last several years of life: for ribs around 2–5 years (Frost, 1969; Parfitt, 2002), and potentially decades for long bones such as femur (Hedges et al., 2007; see Chapter 2). Therefore, the isotopic ratios here reflect an average of possible differences due to changes in diet or location.

As discussed in Chapter 2, historical evidence indicates that animal product consumption would have been low among the poor, although perhaps higher in rural areas. Evans' (1980) dietary reconstruction (Table 2.1) suggests adequate protein quantities, including 25% of protein from animal sources, would have been possible for the rural poor. We can test whether negligible protein consumption is appropriate based on the isotopic evidence presented here by examining the proportion of animal protein in the diet using isotopic models.

Estimating the animal protein fraction from human–animal Δ^{15}N differences is problematic because of the assumptions that must be made. Hedges and Reynard (2007) presented different models for working with these assumptions. Model 1: The standard model assumes that a 100% animal protein diet in humans would be 4‰ higher than the measured animal δ^{15}N value. Model 2: If crops fed to humans were 1‰ higher than the fodder fed to animals, human δ^{15}N would overestimate the animal fraction in the diet. Model 3: If, in addition to 2, the human–animal Δ^{15}N increase was 5‰ rather than 4‰, the animal protein fraction would be further overestimated.

First we can define a number of variables for the calculated estimate of F_A, the animal fraction of the diet. These variables are defined relative to collagen, such that the isotopic ratios of a theoretical 100% marine diet are the isotopic ratios that would be observed in the collagen of a human consuming such a diet.

> $\delta^{15}N_H$ and $\delta^{13}C_H$ are the individual human collagen isotopic ratios.
>
> $\delta^{15}N_A$ and $\delta^{13}C_A$ are the isotopic ratios of the animal baseline, however it is defined. For Roman Italy, I have used -20.7‰ and 4.6‰, the mean values of the faunal samples from Italy (Chapter 5)
>
> T_N is the ‰ trophic level enrichment expected between humans and their food, frequently assumed to be 3−5‰. In Hedges and Reynard (2007) this variable was assumed to equal 4‰ or 5‰ depending on the model.

The simplest model states that the animal protein fraction is derived from the δ^{15}N of the faunal baseline relative to the trophic level enrichment estimate:

$$F_A = (\delta^{15}N_H - \delta^{15}N_A)/T_N \tag{7.1}$$

When this model is applied to the Roman data from Italy for coastal and inland sites, assuming $T_N = 4$‰, it provides an unrealistically high estimate of the animal protein fraction. In the first model of Figure 7.2, the majority of individuals from coastal sites have high enough δ^{15}N that the estimated animal protein fraction is well above 100%. Note that this estimation tends to be higher for coastal sites than for inland sites. This can be adjusted by re-calculating the differences assuming $T_N = 5‰$, as shown in the second model from Figure 7.2. Again, many individuals have animal fraction estimates greater than 100%, which is more true of coastal sites than inland sites.

However as Hedges and Reynard (2007) point out, a correction factor (which I have called P_N) may be added to account for the fact that crops fed to humans may have a higher δ^{15}N on average than fodder for animals due to manuring. The second model can be written as:

$$F_A = (\delta^{15}N_H - (\delta^{15}N_A + P_N))/T_N \tag{7.2}$$

Where $P_N = 1‰$ in this case.

Applying this model to the Roman Italian dataset results in a more realistic estimate of the animal dietary fraction, with a larger proportion of the population falling between the mathematically-valid values of 0 and 100%. We have no way of knowing what P_N may be for Roman Italy. Assuming a larger P_N would shift the entire population to a slightly lower dietary animal fraction estimation, but would not reduce the spread in the data. It would also not explain why individuals from coastal sites have higher animal dietary fractions than individuals from inland sites, since the availability of terrestrial meat at these two locations is theoretically equal. These shortcomings must be addressed by examining a factor which affects high δ^{15}N individuals more than low δ^{15}N individuals: marine fish consumption. It is possible to estimate the marine protein fraction independently from δ^{13}C. We may do so by defining more variables:

> P_C is a correction factor applied to human crops versus animal fodder, similar to P_N. In the absence of information to the contrary, this can be assumed to be zero, but in reality may differ depending on watering strategies (e.g. Ferrio et al., 2005).
>
> T_C is a factor reflecting the slight trophic level enrichment in δ^{13}C between a 100% terrestrial plant and a 100% terrestrial animal diet of about $1 - 1.5‰$. Since the animal fraction of the diet is the

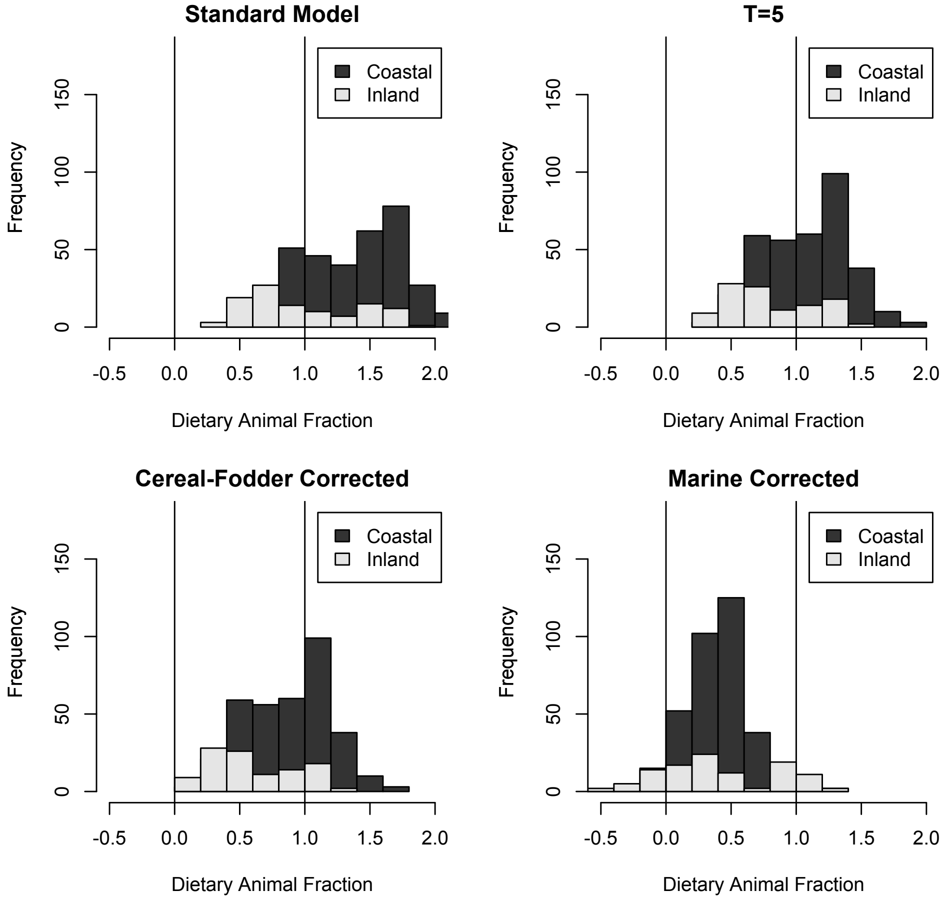

Figure 7.2: *Reconstructions of dietary animal fraction for all Romans in Italy based on four different calculations. All calculations assume* $\delta^{15}N_A = 4.6$*,* $\delta^{13}C_A = -20.7$ *and* $T_C = 0.5$*. Models are: (top to bottom, left to right): 1) The Standard Model:* $T_N = 4$*, 2)* $T_N = 5$*, 3)* $P_N = 1$*, 4) Corrected by* F_M

variable being calculated, this must be estimated. A value of 0.5‰ introduces an uncertainty of ±0.5‰

$\delta^{13}\mathrm{C}_T$ is the δ^{13}C ratio of a 100% terrestrial diet (plant and animal), which equals $\delta^{13}\mathrm{C}_A + P_C + T_C$

$\delta^{13}\mathrm{C}_M$ is the δ^{13}C ratio of a 100% marine diet, which is likely to be around −12‰ (Richards and Hedges, 1999).

$\delta^{15}\mathrm{N}_M$ is the δ^{15}N ratio of a 100% marine diet, which may be highly variable depending on the trophic level of the species consumed (Richards and Hedges, 1999). As discussed above this was initially chosen to be 18‰, but the effect of a lower δ^{15}N ratio will be considered below.

We can estimate the marine fraction of the diet (F_M) as follows:

$$F_M = (\delta^{13}C_H - \delta^{13}C_T)/(\delta^{13}C_M - \delta^{13}C_T) \tag{7.3}$$

and can then incorporate F_M as a correction factor to estimate F_A:

$$F_A = (\delta^{15}N_H - (\delta^{15}N_M \times F_M)) - (\delta^{15}N_A + P_N))/T_N \tag{7.4}$$

Equation 7.3 creates a linear estimate of the marine contribution to the diet, based on δ^{13}C. The marine protein fractions estimated from this calculation are shown in the first two examples in Figure 7.3. Some humans from inland sites have δ^{13}C lower than $-20.2‰$ ($= \delta^{13}\mathrm{C}_A + T_C$). Therefore the estimated marine protein fraction is negative. This is the mathematical result of the estimates used for $\delta^{13}\mathrm{C}_A$ and T_C. These parameters were estimates, and the negative F_M estimate suggests the calculations require adjustment. It is likely that individuals with such low δ^{13}C also had zero marine consumption. Since using negative numbers in the next calculation would overestimate F_A, I have replaced $F_M < 0$ with 0. The effect of constricting the F_M estimate to only positive values is shown in the third and fourth examples in Figure 7.3. There are no differences for coastal sites, since all F_M estimates for coastal sites were originally positive.

The expected contribution to δ^{15}N based on such a level of marine consumption is then subtracted from the animal dietary fraction estimate in equation 7.4. The effect of this calculation is illustrated in the fourth diagram in Figure 7.2. This calculation provides a much-improved estimate of the dietary animal fraction: the values fall realistically below 100%, and coastal and inland sites have similar distributions.

7.1.2 Roman dietary isotopic models in context

These models must be used for interpretation cautiously. They are not intended to represent a definitive dietary quantification. The T_N-corrected, P_N-corrected, and F_M-corrected calculation is not the only appropriate possibility.

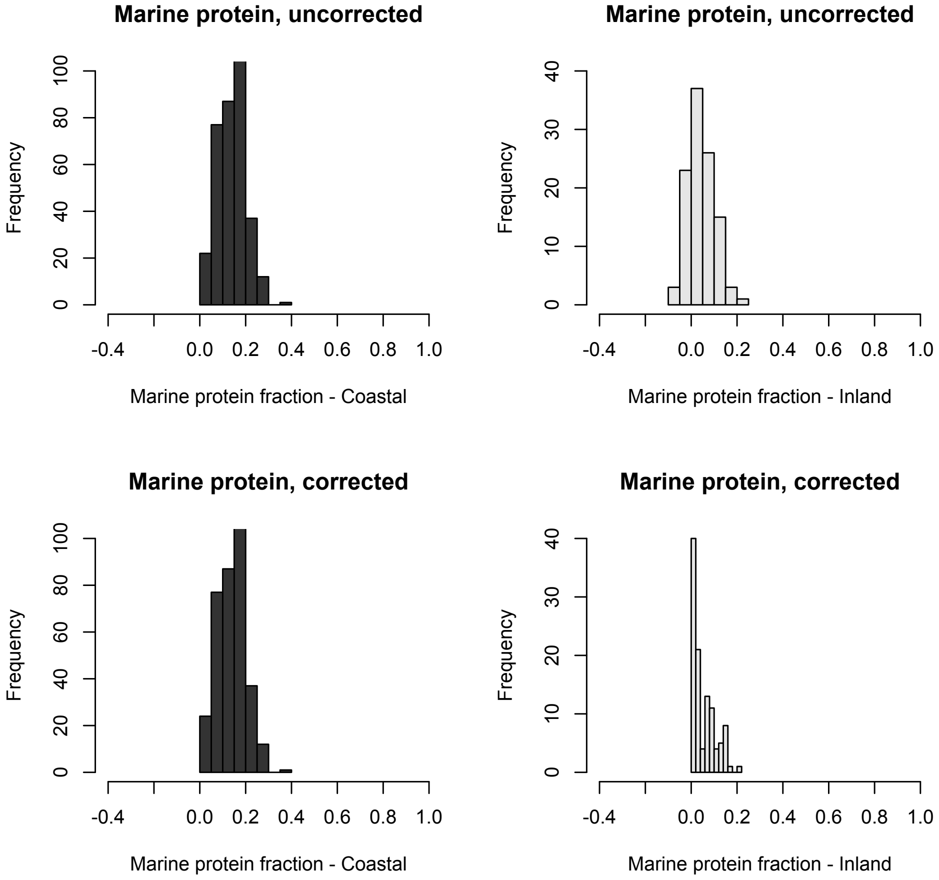

Figure 7.3: *Reconstructions of dietary marine protein fraction (F_M) for all Romans in Italy. For the top two diagrams, $F_M = (\delta^{13}C_H - \delta^{13}C_T)/(\delta^{13}C_M - \delta^{13}C_T)$. For the lower two, $F_M < 0$ has been overwritten as 0.*

The calculations used are able to successfully reconstruct plausible diets for the majority of the population, but clearly do not provide an adequate dietary reconstruction for those few individuals with extremely low or high F_A estimates. These individuals lying outside the explanatory bound of the model may be explained by the uncertainties in the variables used for the calculations, and due to inter-individual differences. Other factors that were not considered may play a significant role, for example, freshwater fish. Adjustments could be made to any of the initial variables, or model parameters that would affect the model's fit. The calculations are valuable, however, as a heuristic device, since it illustrates what may be plausible, and it emphasizes the number of isotopic factors that must be considered in making dietary reconstructions.

What can we learn from these calculations? First, they suggest that there is not necessarily anything 'anomalous' about the high δ^{15}N ratios reported from Roman Italy. Despite the uncertainty of estimating a faunal baseline for Roman Italy, they are broadly compatible with a realistic level of animal protein consumption, but only if additional factors are taken into account. These additional factors are: 1) assuming a Δ^{15}N food-to-human trophic level increase of 5‰ rather than 4‰; 2) assuming that human cereals were 1‰ higher in δ^{15}N compared to animal fodder; 3) and correcting for marine protein consumption, assuming isotopic endpoints for a 100% marine diet of $\delta^{13}\mathrm{C} = -12$ and $\delta^{15}\mathrm{N} = 18$‰.However, there are two other factors that could provide an alternative explanation for high Roman δ^{15}N ratios in Italy: 1) the inclusion of non-protein carbon in collagen, and 2) a lower δ^{15}N for fish in the Mediterranean.

As discussed in Chapter 3, it was suggested that diets would have to contain a low absolute amount of protein before non-carbon protein would make a large contribution to collagen (diets containing around $5 - 12\%$ protein by weight; Jim et al., 2006). It is, However, it is important to investigate the potential difference in dietary reconstruction between assuming that the collagen reflects 100% protein, 75% protein or 50% protein. At the same time, we must also examine the effect of chosing a lower δ^{15}N ratio of around 12‰ to represent a 100% marine diet.

Figure 7.4 estimates collagen δ^{13}C and δ^{15}N ratios for a hypothetical mixture of dietary protein sources (plant, animal and marine) and compares them to the actual measured collagen isotopic ratios from Italy (all periods). Here the three 100% dietary endpoints are identical to those used Standard Model above, except that the δ^{15}N ratio of a 100% marine diet is assumed to be 12‰ rather than 18. The dietary mixture in this Figure illustrates the effect of assuming that 100% of collagen carbon reflects dietary protein. It suggests that the 100% estimates chosen do not result in realistic dietary mixtures, with the

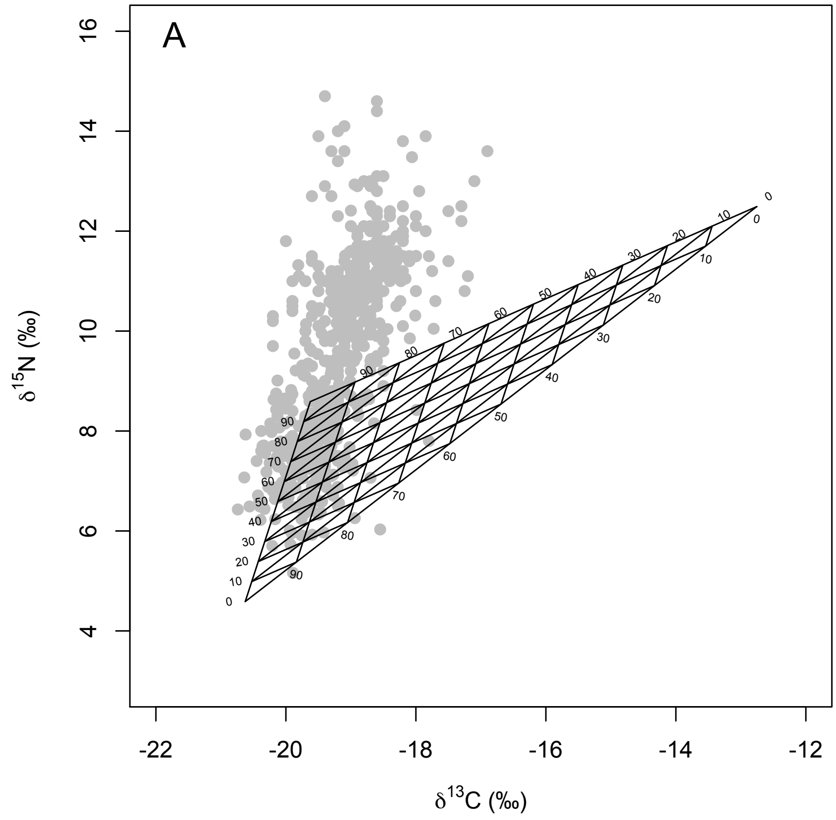

Figure 7.4: *Estimated collagen $\delta^{13}C$ and $\delta^{15}N$ for varying mixtures of plant, animal and marine protein (black lines), showing the effect of assuming* 100% *of collagen is derived from protein. Endpoints are derived from actual Roman Italian fauna, as for the standard model above, except that the $\delta^{15}N$ ratio of a* 100% *marine diet is* 12‰. *Actual human $\delta^{13}C$ and $\delta^{15}N$ ratios from Italy shown in grey.*

actual human δ^{15}N being much higher, and the δ^{13}C ratio being much lower than would be predicted based on the dietary endpoints.

Assuming that only B 75% (Figure 7.5) or C 50% (Figure 7.6) of collagen carbon is derived protein sources dramatically increases the apparent contribution of marine resources, meaning that less of the high δ^{15}N ratios need to be explained by animal protein consumption. In this case the non-protein carbon was assumed to be carbohydrate, with δ^{13}C identical to terrestrial animals. The fraction of carbon dervied from non-protein sources was assumed to be

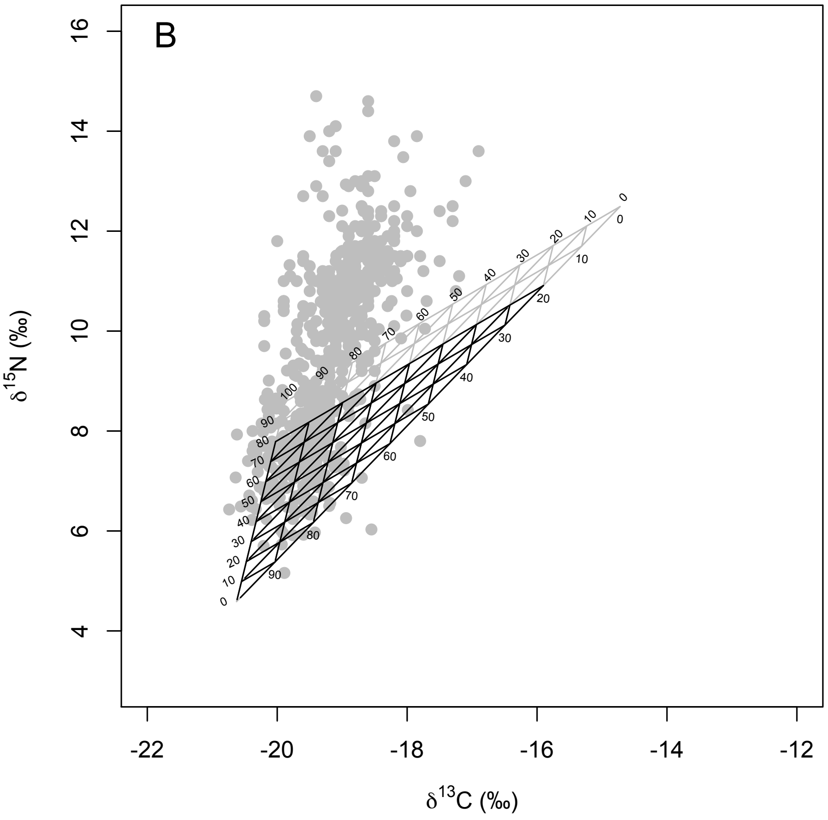

Figure 7.5: *Estimated collagen $\delta^{13}C$ and $\delta^{15}N$ for varying mixtures of plant, animal and marine protein (black lines), showing the effect of assuming* 75% *of collagen is derived from protein. Endpoints are derived from actual Roman Italian fauna, as for the standard model above, except that the $\delta^{15}N$ ratio of a* 100% *marine diet is* 12‰. *Actual human $\delta^{13}C$ and $\delta^{15}N$ ratios from Italy shown in grey.*

consistent for all dietary combinations.[3] Accounting for the contribution of non-protein (carbohydrate) resources to collagen produces dietary estimates that are much more consistent with the isotopic data from Roman Italy. This assumption dramatically increases the amount of marine resources estimated to have been consumed.

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[3] In reality this is not possible to calculated three-way mixing in in this way, because as the plant protein portion of the diet decreases close to zero, it would be impossible for the carbohydrate carbon fraction in the diet to remain high. For this reason, mixtures are only highlighted for cases where plant protein > 20%.

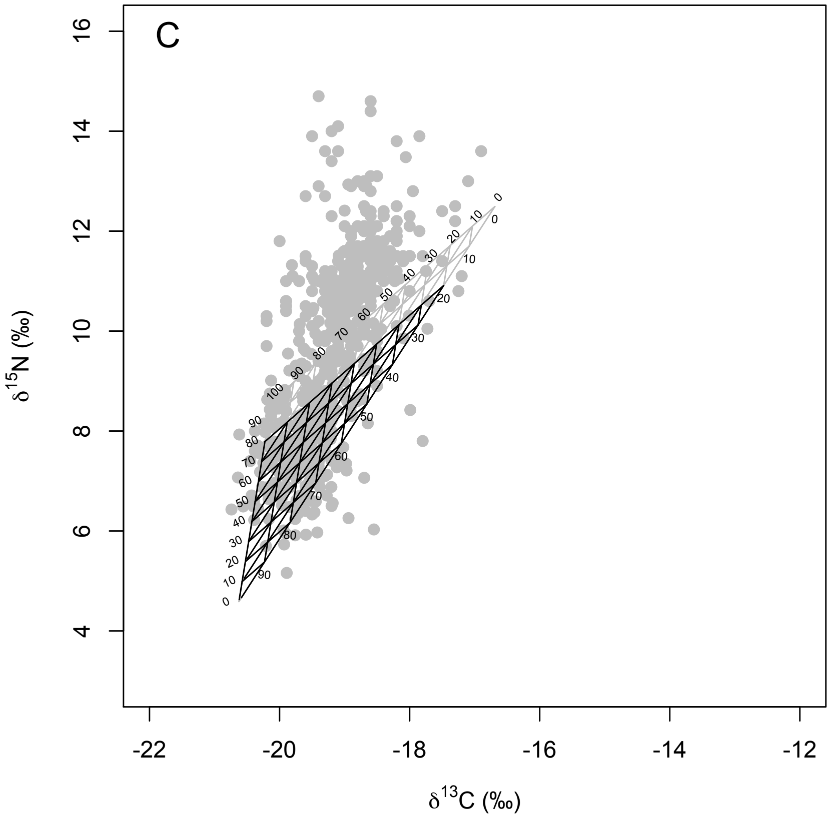

Figure 7.6: *Estimated collagen δ^{13}C and δ^{15}N for varying mixtures of plant, animal and marine protein (black lines), showing the effect of assuming* 50% *of collagen is derived from protein. Endpoints are derived from actual Roman Italian fauna, as for the standard model above, except that the δ^{15}N ratio of a* 100% *marine diet is* 12‰. *Actual human δ^{13}C and δ^{15}N ratios from Italy shown in grey.*

However, many of the human δ^{15}N ratios are significantly higher than the dietary mixtures illustrated by the triangular mixing lines in Figures 7.5 and 7.6. This suggests that, in addition to a significant portion of carbon being derived from non-protein sources, the estimatated collagen δ^{15}N ratios of 100% plant, animal (and possibly also marine) diets are higher than the δ^{15}N ratios typically meausred. The δ^{15}N ratios of the Italian fauna reported above may provide an inaccurately-low estimate of the δ^{15}N ratios of the plants and animals actually consumed by humans. This was also noted when comparing intra-site Δ^{15}N ratios in Chapter 6. The δ^{15}N ratios of plants consumed by humans may be higher than those consumed by the animals reported here if there were differences in the manuring regime (Bogaard et al., 2007; Fraser et al., 2011) or if they plants were grown in a different environment where high δ^{15}N was the result of aridity. Since the inhabitants of the city of Rome were known to receive shipments of grain from Sicily, Egypt and North Africa (Garnsey, 1998), the effect of imported food should not be discounted. The effect of the consumption of legumes (lower in δ^{15}N) by either animals or humans has also not been considered, since it could not help explain the relatively high δ^{15}N in humans, but this omission introduces further uncertainty. Overall, it seems likely that both factors that affect our interpretation of human and animal δ^{15}N (such as manuring or trophic level estimates) as well as the effect of non-protein carbon in collagen need to be taken into account. At present it is not possible to say which combination of factors plays a greater role, introducing further uncertainty in dietary estimates.

The calculations of animal protein fraction presented above may be constructive for addressing questions related to Roman diet and economy. First, on the basis of the marine protein fraction estimation (Figure 7.3), the available isotopic data is consistent with a Roman diet containing generally less than $20 - 25\%$ marine protein by weight for coastal sites (although this estimate would increase as the non-protein carbon fraction in collagen increases). At inland sites, the isotopic data suggests negligible amounts of marine protein were consumed by most individuals (about 5% marine protein or less, again based on 100% routing of protein to collagen carbon). There was, however, considerable overlap between coastal and inland sites. The calculations suggest that the isotopic evidence is consistent with some individuals from inland sites consuming marine protein in quantities comparable with individuals from coastal sites. All of this information accords with the initial impression of the raw individual isotopic ratios, with small but significant differences in human δ^{13}C between inland and coastal sites in Roman Italy.

Whereas the simpler animal protein fraction calculations suggested unrealistically high levels of animal protein consumption for Roman Italy, the F_M-corrected calculation gave the most appropriate F_A reconstruction for the entire Roman Italian population. Overall, the size of F_A is relatively high, and inconsistent with the historical evidence (Chapter 2) which suggested the average Roman would have consumed relatively small amounts of animal protein. An estimated animal protein fraction of $12 - 17\%$ can be derived from rations of bread and pork given to the urban poor from the 3rd century AD onwards.[4] Evans (1980) attempted to provide a more realistic dietary reconstruction by considering a wider variety of foods (especially nuts, wine and olive oil) that may have been available to the rural poor. Of the protein component in Evans' diet, 24% is of animal origin (cheese and egg). His reconstruction includes neither fish, nor legumes, nor salt pork, which could have also been significant dietary components. Although Evans' estimate is not intended to be extrapolated to Roman diet as a whole, his emphasis on the consumption of animal products is consistent with the isotopic evidence.

The isotopic results from Roman Italy suggest that, even accounting for corrections due to trophic level estimates, cereal-fodder differences, and small amounts of marine protein consumption, most individuals consumed more animal protein than suggested by the historical evidence. Salt pork, sausages, eggs and cheese may have been widely available, but to varying degrees (Evans, 1980; Frayn, 1995; Garnsey, 1999). The variation in human δ^{15}N is not solely attributable to differences in marine protein consumption. The wide range of reconstructed F_A estimates is consistent with a large amount of inter-individual variation in animal protein consumption. In Chapter 5, I observed intra-site groupings in adult human δ^{15}N at Casale del Dolce, Osteria della Fontana and ANAS, which is reflected in the bimodal distribution of calculated F_A values in the fourth diagram in Figure 7.2. While environmental and inter-individual

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[4] The 500g of bread per day would yield about 50g of protein. The 25-35 g of salt meat would have yielded 7-10g of protein (Garnsey, 1998).

variation is an obvious compounding factor, inter-individual differences in animal protein consumption are also likely to be significant, and may be related to status or mobility.

As discussed in Chapter 5, the distinction between coastal and inland sites is problematic, since Rome is located 25km from the modern coastline,[5] but its position on the Tiber gave it unimpeded access to coastal resources. Sites located in or near Rome have individuals with higher δ^{15}N values typical of other coastal sites (Isola Sacra, Pompeii, and Civitanova Marche). However, the ability of Rome's residents to consume this high δ^{15}N diet may be unrelated to the city's proximity to the coast, but instead may reflect the role that urbanization plays in concentrating high δ^{15}N food resources such as meat and fish (see 7.5 below). Recall that in Chapter 5 there was a large and significant effect for δ^{15}N (effect size = 2.4‰, $p = 0.0002$) when Italian sites were classified as urban or rural. The effect for δ^{13}C for Urban/Rural sites was similar to the effect for Coastal/Inland. This can also be illustrated by re-running the calculations in Figure 7.2 above, but for Rural and Urban sites (see Figure 7.7). Since δ^{15}N is significantly higher for humans at urban sites compared to rural sites, the estimate of the animal fraction of the diet also tends to be higher for urban sites compared to rural sites.

Other factors may also explain why urban sites have higher δ^{15}N. Freshwater fish is a potentially high δ^{15}N food source that was not considered in the dietary calculations above. It could have been an important protein supplement for the poor, an argument used by Rutgers et al., (2009) to explain high δ^{15}N among an early Roman Christian population who were likely economically disadvantaged. The pressure of urbanization was also used to explain higher δ^{15}N at classical Thebes compared to earlier and later periods, when high δ^{15}N foods were sought to supplement the increasingly limited terrestrial foods of lower δ^{15}N (Vika, 2011). In the Mediterranean, urbanization and proximity to the coast are linked, making it relatively difficult to disentangle these related

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[5] As is ANAS.

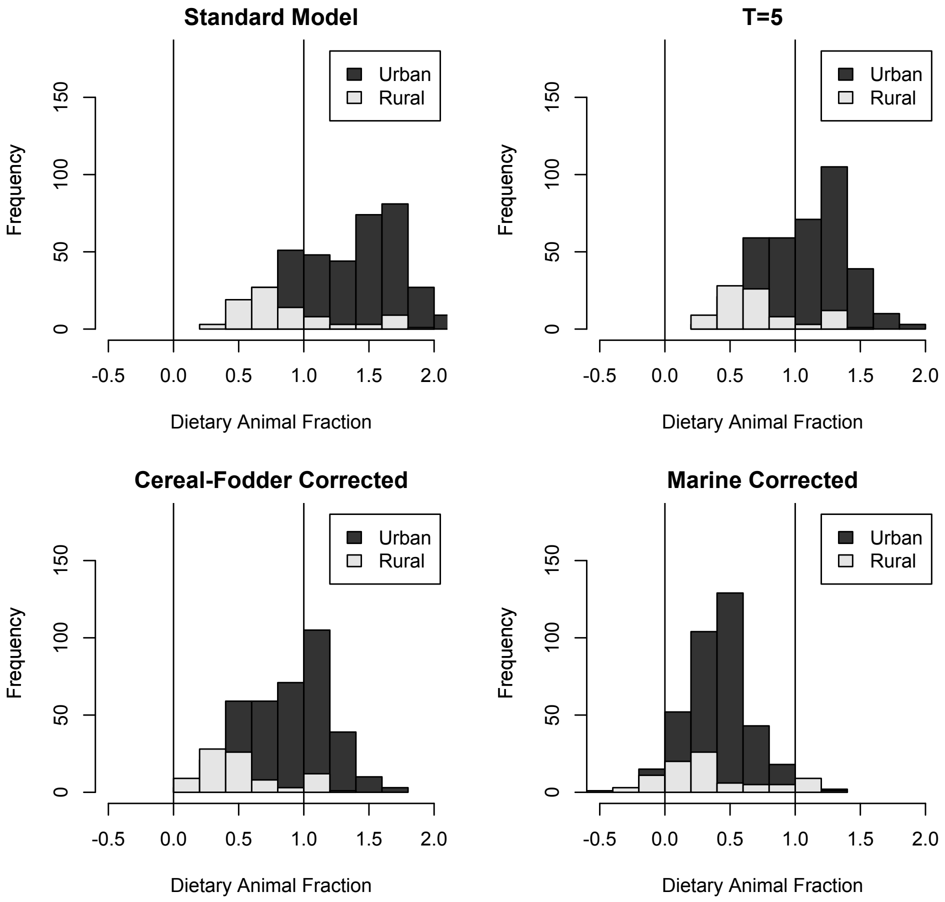


Figure 7.7: *Reconstructions of dietary animal fraction for all Romans in Italy from Urban and Rural sites based on four different calculations. All models assume* $\delta^{15}N_A = 4.6$*,* $\delta^{13}C_A = -20.7$ *and* $T_C = 0.5$*. Models are: (top to bottom, left to right): 1) The Standard Model:* $T_N = 4$*, 2)* $T_N = 5$*, 3)* $P_N = 1$*, 4) Corrected by* F_M*.*

dietary influences. It is also difficult to quantitatively assess relative degrees of urbanization in the archaeological record. Craig et al. (2009) noted that the overall higher δ^{15}N at Isola Sacra compared to Velia may be related to the importance of the site, as the port of Rome, compared to the relatively modest port at Velia. Overall these results suggest that some coastal populations in the Roman empire did not consume discernable amounts of marine resources, while some individuals from inland urban areas were able to regularly consume them. Dietary patterns in complex societies result from an interaction of a variety of social and economic factors (Gumerman, 1997). Factors such as urban markets, mobility, and social status may have affected food availability, producing the patterns observed here.

Initially, this study sought to address three related questions about Roman economy and diet in order to better understand the nature of the Roman–Medieval dietary transition. Although the meta-analysis had been designed to look for comparative studies of contemporary Roman and non-Roman populations, there were no adequate studies with which to address the question of ideological differences between Roman and non-Roman food practices. The isotopic evidence for Roman Italy suggests there were significant Coastal/Inland and Urban/Rural dietary differences. The calculations of animal protein fraction in the diet suggest that meat consumption may have been higher than expected for the average Roman, and that the model of a grain-based, highly-integrated economy is not uniformly appropriate for south-central Italy. This suggests that the Roman diet, economy, agricultural practices and food culture may have been more similar to Early Medieval practices than was originally hypothesized. The implications of this conclusion for the broader issue of the Roman–Medieval dietary transition are explored in more detail below.

7.2 Late Antique Christianity and Diet Change: Why is Marcellino e Pietro different from St Callixtus?

The relationship between Christianity and diet can be examined by comparing the results from the 3rd to 5th-century group from the catacombs of SS Marcellino e Pietro outside of Rome to other nearby or contemporary sites. Rutgers et al. (2009) reported isotopic ratios from the early Christian (3rd- to 5th-century AD) catacombs of St Callixtus, outside Rome. On the basis of the relatively high δ^{15}N and relatively terrestrial δ^{13}C, and combined with evidence for potential freshwater radiocarbon effects, the authors suggested that these early Christians consumed detectable quantities of freshwater fish. The results from St Callixtus are significantly different from the 14th-century individuals from the Palazzo della Cancelleria in Rome analysed by Salamon et al. (2008). At Palazzo della Cancelleria, both δ^{13}C and δ^{15}N were high enough to indicate that significant quantities of marine fish were consumed, which the authors suggested was related to a post-AD 1000 increased availability of fish. This suggestion was based on the comparison with the 6th-century inland rural site of Castro dei Volsci which had much lower δ^{13}C and δ^{15}N.

As described in Chapter 5, the individuals buried in the catacombs of Marcellino e Pietro outside of Rome have generally high δ^{13}C (mean $= -19.7 \pm 0.4‰$) and high δ^{15}N (mean $= 10.5 \pm 1.4‰$), indistinguishable from the 14th-century individuals from Palazzo della Cancelleria. Individuals from Marcellino e Pietro also had significantly higher δ^{13}C compared to the early Christian catacombs of St Callixtus, and significantly higher δ^{13}C and δ^{15}N compared to the rural population of Castro dei Volsci (recall Figure 5.14). This difference is consistent with a significantly higher consumption of both animal meat and marine fish in Late Antique Rome compared to Late Antique rural Lazio. These data are consistent with the zooarchaeological evidence for decreased pork consumption in Late Antiquity, which occurred earlier at rural sites, while major cities, especially Rome, continued to be able to procure these products (Arthur, 2004; Barnish, 1987; King, 1999).

The difference in δ^{13}C between St Callixtus and Marcellino e Pietro also requires discussion. The higher δ^{13}C in the Marcellino e Pietro group presented here is likely due to the consumption of marine fish, as opposed to the freshwater fish which was hypothesized for the St Callixtus group (Rutgers et al., 2009). Evidence from Diocletian's Edict of Maximum Prices and other literary references suggest freshwater fish was cheaper and socially inferior compared to marine fish, which could only be consumed fresh by the very wealthy (Curtis, 1991; Gowers, 1993; Nutto, 1995; Purcell, 1995). The dietary difference may be related to a higher social status for the individuals from the Marcellino e Pietro catacombs. In the period between the 3rd and 5th centuries represented by the group from St Callixtus and the 5th- to 6th-century dates of the Marcellino e Pietro group, Christianity assumed greater prominence and acceptance, and ecclesiastical authorities took over much of the administrative functions left by the power vacuum in late Antique politics (Le Goff, 2007). Donations of land to the church brought not only wealth (Christie, 2006), but access to expensive foods like meat. Here we may see the transition from the freshwater fish-based diet of the poor, socially-marginalized Roman Christians in the 3rd- to 5th-centuries (as suggested by Rutgers et al., 2009), to elevation of Christians to the most powerful positions in society by the 5th and 6th centuries, with a diet befitting their status.

7.3 The evidence for diet change in Early Medieval Italy

The primary goal of this study was to examine the isotopic evidence for Early Medieval diet and to determine whether it was significantly different from Roman diet. I attempted to make comparisons both on a local scale, using data from a 1500-year period in the same area of Central Italy, and on a continental scale, using data from previously published studies from across Europe. In addition to looking for general patterns in diet change, I was also interested in examining isotopic differences related to rural/urban differences and climate. This section examines these patterns in more detail.

7.3.1 Evidence for Early Medieval Diet change on local and continental scales

If meat consumption was significantly higher in the Early Medieval period, it is likely that δ^{15}N in humans would be higher than in the Roman period. This hypothesis was examined using both local- and continental-scale evidence. First, in order to control for possible geographic effects, I compared individuals from sites within a relatively small region of central Italy. Roman Osteria

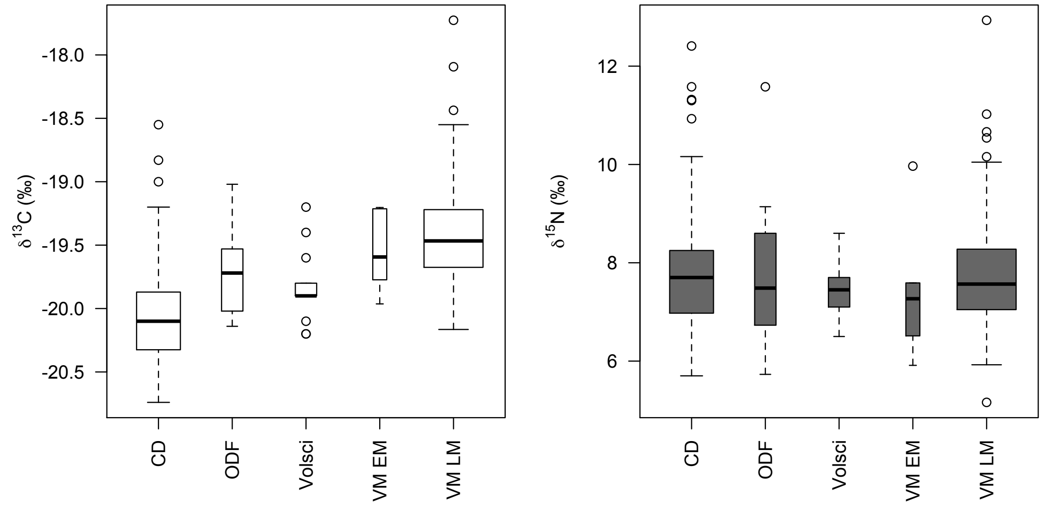


Figure 7.8: *Box plot of changes in $\delta^{13}C$ and $\delta^{15}N$ for the Sacco-Liri Valley, Italy c. AD 1–1500. CD is Casale del Dolce (1st-4th century AD), ODF is Osteria della Fontana (1st century AD), Volsci is Castro dei Volsci (6th century AD, Salamon et al., 2008), VM EM are the Early Medieval individuals from Villamagna (c. 800–1000), VM LM are the Late Medieval individuals from Villamagna (c. 1000–1500).*

della Fontana and Casale del Dolce were compared to the previously published humans from 6th century Castro dei Volsci (Salamon et al., 2008) and the Early and Late Medieval individuals from Villamagna. These sites are all located within a 30km straight-line distance of one another in the same river valley.

Figure 7.8 illustrates the results presented in Chapter 5. There are no significant differences in δ^{15}N between any of these sites (see Table B.2). This does not support the hypothesis that meat consumption increased in the Early Medieval period. The limited number of samples from the Early Medieval period from Castro dei Volsci and Villamagna are indistinguishable in δ^{15}N from the nearby Roman and Late Medieval sites. However as discussed in Chapter 5, there are significant inter-site differences in δ^{13}C between Osteria della Fontana and Villamagna (difference of 0.42‰ $p < 0.01$) and between Castro dei Volsci and Villmagna (difference of 0.6‰, $p < 0.001$), which are apparent in Figure 7.8. The evidence suggests that δ^{13}C in humans may have increased slightly over time, while δ^{15}N remained the same. Individuals from the three sites that date prior to AD 800 (Casale del Dolce, Osteria della Fontana and Castro dei Volsci) have lower δ^{13}C compared to the Early Medieval individuals from Villamagna (dated c. 800 to 1000) and the Late Medieval individuals (c. 1000 to 1500). The potential cause of this Late Medieval δ^{13}C shift will be discussed below.

In Chapter 6 I presented the results of a mixed multi-level model to examine differences between Roman, Early Medieval and Late Medieval humans from across Europe. At the site level, this model took into account random inter-site variation, location (Mediterranean, Central Europe, Northern Europe or England) and proximity to the coast (Coastal or Inland), as well as considering the sex of the individual (M, F, U). Controlling for all these factors, the model found that there was a significant effect for Date. Early Medieval humans had slightly but significantly lower δ^{13}C and δ^{15}N compared to the Roman and Late Medieval periods. For δ^{13}C the effect size for EM-R was 0.32‰ ($p = 0.0003$) and 0.49‰ for EM-LM ($p < 0.0001$). For δ^{15}N the effect size was 0.51‰ for EM-R ($p = 0.003$) and 0.74‰ for EM-LM ($p < 0.0001$). Roman and Early Medieval individuals in the meta-analysis were more similar than Early Medieval and Late Medieval individuals.

However, it was also observed that this chronological effect is dominated by the pattern occurring in England, which makes up a significant proportion (37%) of the total human dataset. When the models are run separately for different locations, there is no significant effect through time for the Mediterranean (see Table 6.10). In addition, comparing the humans with the results of the meta-analysis for faunal samples suggests the human variation in δ^{13}C and δ^{15}N through time may track a similar trend in faunal isotopic ratios.

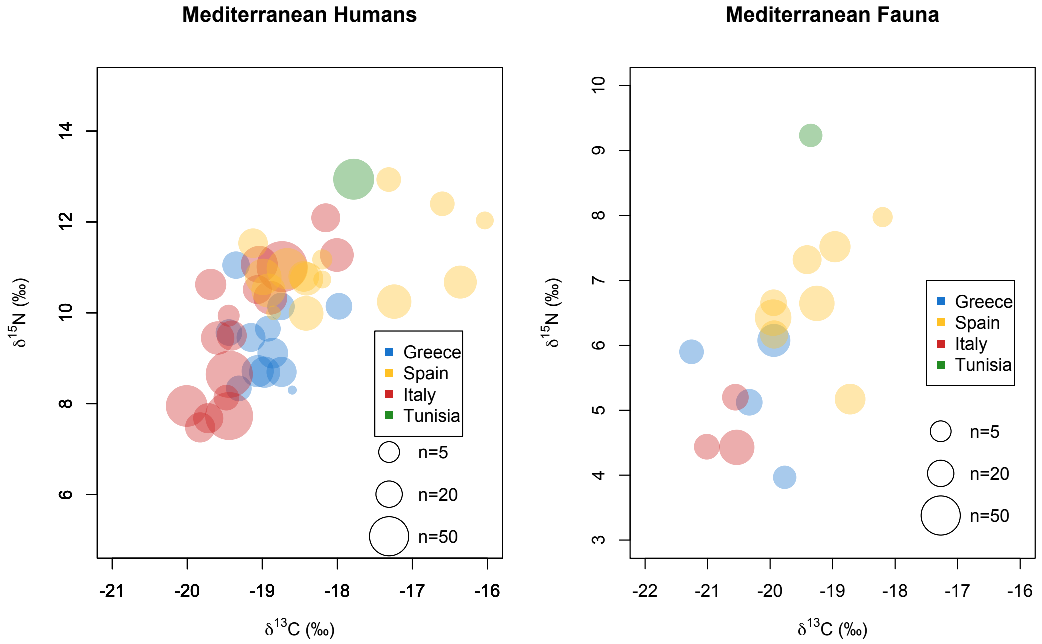
The initial hypothesis that δ^{15}N would increase in the Early Medieval period is not supported by the results of the meta-analysis, and in some cases (especially England) the opposite is true. Multiple confounding factors could be contributing to this pattern, which I will examine in the following sections.

There may have been changes in the isotopic baseline through time, which make a direct comparison between periods inappropriate. These changes could be due to overall climate conditions (cooling temperature, increasing rainfall) or agricultural practices (different manuring regimes, land clearance). These patterns may also represent genuine dietary differences. I will examine the degree to which the isotopic data could be reconciled with the hypothesized dietary trend by investigating potential diets where high δ^{15}N foods (fish) in a diet with low amounts of meat could have been replaced by diets with a large proportion of meat and fewer high δ^{15}N foods. Finally, I will discuss whether a more nuanced view of the economic circumstances that gave rise to the notion of meat-laden Dark Age peasants may be the most appropriate explanation.

7.3.2 Confounding factors: Climate, geography and agricultural variability through time

There are two ways in which climate and geography could affect the interpretation of the isotopic results presented in Chapters 5 and 6. First, there could be inter-site isotopic differences due to climate or geography, which are not accounted for in the statistical models. This may be especially relevant for the Mediterranean studies included in the meta-analysis, which originate from diverse locations. Recall from Chapter 6 that the Mediterranean humans and fauna had the widest variation in δ^{13}C and δ^{15}N out of any of the four regions. Second, climate changes through time may have affected the baseline isotopic ratios in the ecosystem.

Within the Mediterranean, there are clear geographic differences (see Figure 7.9). Italian fauna and humans tend to have the lowest δ^{13}C and δ^{15}N, while isotopic ratios become progressively higher as one moves to Greece, Spain, and then Tunisia. These changes correspond well with known climatic differences between these regions. Italy has the coolest, wettest climate of the Mediterranean countries, while Tunisia is particularly hot and dry. Such climatic differences correlate with the measured isotopic trends. As discussed in


Mediterranean Humans

Mediterranean Fauna

Figure 7.9: *Plot of $\delta^{13}C$ and $\delta^{15}N$ humans and fauna from the Mediterranean, by country*

Chapter 3, increasing temperature and aridity results in increasing δ^{13}C and δ^{15}N, especially when plants are water-stressed. These geographic differences can also be illustrated by drawing loess-smoothed curves for human and faunal isotopic ratios and comparing the variation according to Latitude/Longitude (see Figure 7.10) or Altitude (see Figure 7.11).[6]

These confounding climatic variables may partly explain the variation (and lack of variation) in the Mediterranean by period. When the Mediterranean humans were modelled separately, the only significant chronological effect is that Late Medieval humans had higher δ^{13}C compared to Early Medieval humans (effect size 0.65‰, $p < 0.0001$).[7] This effect is largely due to the high δ^{13}C of the Late Medieval Spanish sites, likely the result of C4 plant consupmtion. The

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[6] LOESS is locally weighted scatterplot smoothing. It is a method for plotting a smooth curve through a series of data points, similar to linear regression. The smoothed value is calculated as the weighted quadratic least squares regression. Calculations were performed using the loess() function in [R].

[7] Note that Figure 6.16 does not fully illustrate this effect. It is only an approximation of the data based on two variables (Loccode and Datecode) whereas the statistical model also incorporates Coastal/Inland, Sex and random inter-site variation

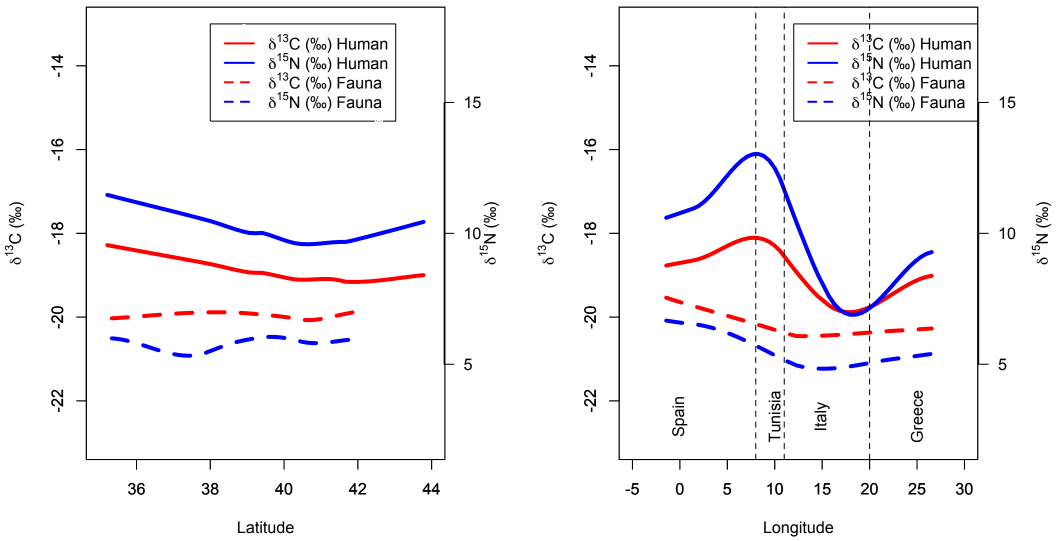

Figure 7.10: *Plot of loess-smoothed curves for variation in human and fauna $\delta^{13}C$ and $\delta^{15}N$ across the Mediterranean, by latitude and longitude. Note that the loess curve is a simplification of a widely dispersed dataset.*

consumption of C4 plants, however, is also culturally determined, as noted by Mundee (2010) who found significant differences in δ^{13}C between Islamic and Christian contexts.

It is also possible to incorporate the geographic data (Latitude, Longitude and Altitude) in the mixed, multi-level model (see B.5.2). For δ^{13}C, Longitude is the only significant effect, largely reflecting the significant difference between the relatively high δ^{13}C at Spanish sites, and the lower δ^{13}C for humans at Italian sites. The output of the model for Datecode does not change significantly, except that LM sites have significantly higher δ^{13}C compared to both EM and Roman sites. For δ^{15}N, Longitude is a significant factor, reflecting the same Spain-Tunisia/Italy difference as for δ^{13}C. Altitude also has a significant effect on δ^{15}N, but this may be due to the number of coastal sites that tend to have high δ^{15}N because of marine fish consumption (see Figure 7.11). Note that altitude data was log-transformed to improve the distribution. Although the model can account for geographic and climatic variation, it cannot explain

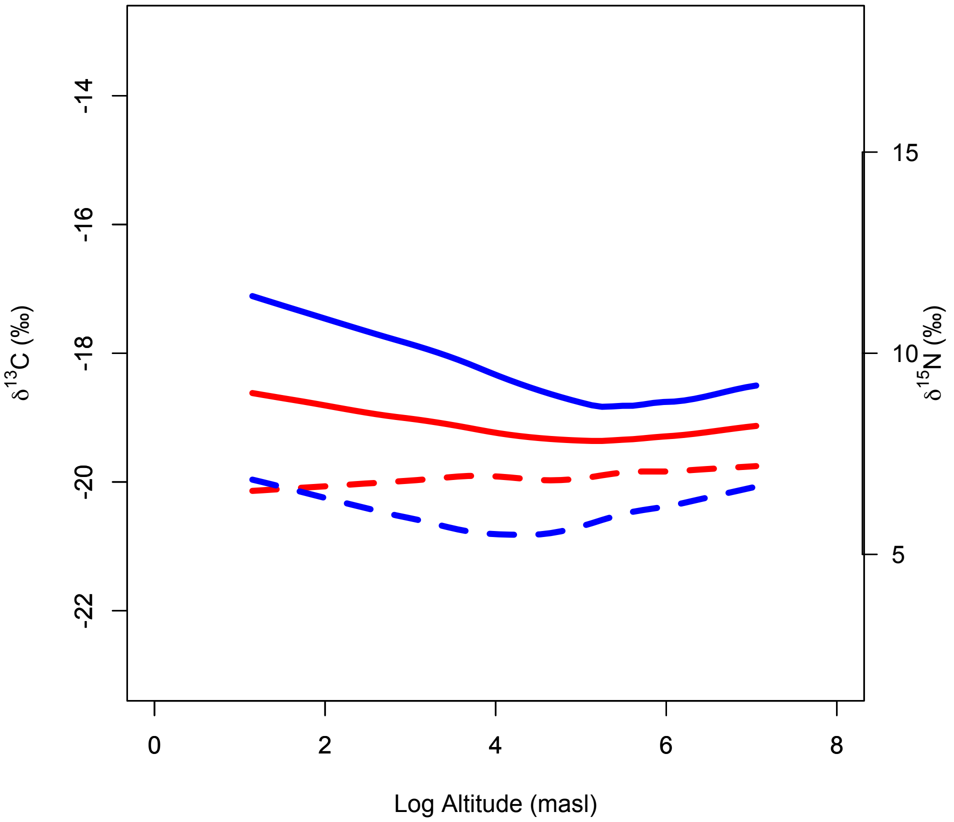

Figure 7.11: *Plot of loess-smoothed curve for variation in human and fauna $\delta^{13}C$ and $\delta^{15}N$ across the Mediterranean, by Altitude (m above sea level) on a logarithmic scale. Note that the loess curve is a simplification of a widely dispersed dataset.*

or correct for it. Additional climatic information would be required. The variability within the Mediterranean shown in Figure 7.9 suggests that this region is not the most appropriate unit of analysis, and that sites are best considered on a more local scale.

Recall from section 2.5 that climate changed significantly over the 1500-year period in question. The period immediately following the end of the Roman Empire was cooler and wetter. Both of these factors would contribute to lower δ^{13}C at the base of the foodchain. An average decrease in temperature of 1°C could lower δ^{13}C by 0.3‰ (Heaton, 1999). Recall that the size of the effect for the difference in δ^{13}C for humans in the entire meta-analysis was 0.32‰ for R-EM and 0.49‰ for LM-EM. Therefore, the difference in human δ^{13}C through time is similar to what might be expected from climate change.

This study attempted to examine the effect of climate change independently, by comparing human isotopic results to an appropriate faunal baseline. When the faunal samples were analysed, there were no significant differences in faunal δ^{13}C through time. However, δ^{15}N tended to be lower for EM fauna compared to Roman and LM fauna. For δ^{15}N the R-EM effect size was 0.76‰ ($p = 0.047$) for the model that aggregated fauna from Central Europe, Northern Europe and England.[8] When the Mediterranean faunal samples were modelled on their own, EM δ^{15}N tended to be lower than Roman and LM, but the differences were not significant owing to the smaller sample size. Comparing the results of the human meta-analysis to the results of the faunal meta-analysis suggests that a significant amount of the variation in human δ^{15}N may be explained by underlying faunal variation, but there is less evidence for such an explanation for variation in δ^{13}C. In 6.3 I also compared intra-site human-faunal Δ^{13}C and Δ^{15}N differences, but since the analysis was at the site-level only, sample sizes were too small to observe significant chronological trends.

Changing agricultural practices over time may also have influenced isotopic ratios at the base of the food chain. It is important to consider how strategies to increase food production for areas and periods of high population density could have affected isotopic ratios. Population density was higher in the Roman period than in the Early Medieval period. Sustaining a high population requires intensification: extracting more resources from either the same amount of labour or from the same area of land (Scarborough, 2006). 'Intensive' agriculture uses high-labour, high-yield strategies (irrigation, high-yield seed varieties, manuring), while 'extensive' agriculture uses a larger area to increase production while maintaining the labour input by expanding arable cultivation to previously unused land, often marginally useful territories. This

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[8] There were no significant differences in faunal isotope ratios between these regions.

pressure to expand or find new, more productive, methods of farming was felt by ancient Mediterranean cities. The Greeks sent men out to colonize new territories whose surplus agriculture would feed the growing numbers in the metropolis (literally 'mother city'). As described in Chapter 2, the Romans increased agricultural output through more intensive farming, and through expanding their agricultural territory throughout the Italian peninsula, and ultimately, across the Mediterranean and much of Western Europe (Garnsey, 1999). The Romans were also able to intensify their resource production by selectively breeding larger animals through time (MacKinnon, 2004). Intensification comes not just from technological developments, but from more complex interactions between social organization, environment and landscape (Scarborough, 2006); however, in the Mediterranean, intensification may not have been the only goal. The dominant practice may have been risk avoidance, rather than intensification alone (Horden and Purcell, 2000).

The availability of nitrogen in the soil was the key limiting factor in Mediterranean agriculture, and the two-year crop rotation cycle was designed to reintroduce as many nutrients as possible into the soil (Spurr, 1986). Animals and crops were likely highly integrated in the ancient Mediterranean, to facilitate the application of manure (Halstead, 1987). Archaeobotanical evidence from southwestern Germany suggests that the trends towards soil acidification and soil deterioration that had occurred since the Neolithic were reversed by widespread manuring in the Roman period (Rösch, 1998). Modern experiments have shown that manuring can affect plant δ^{15}N up to $4-5‰$ (Bogaard et al., 2007; Fraser et al., 2011; see Chapter 3). High δ^{15}N nitrates remain in the soil for several decades, but it seems that soils gradually return to un-manured δ^{15}N over time (Fraser et al., 2011). Such an effect could contribute to changing δ^{15}N in animals and humans from the Roman to the Early Medieval period. The possible magnitude of this effect for potential dietary reconstructions will be considered below.

Recall that there was a moderately significant correlation between δ^{13}C and δ^{15}N for Italian fauna (Pearson's $r = 0.47$, $p = 0.001$), with a regression slope of 0.83. Generally, however, there were no significant correlations between faunal δ^{13}C and δ^{15}N, except for the 12 Roman faunal samples from Central Europe, which had a significant negative correlation. The Italian faunal correlation arises because fauna that tend to have high δ^{13}C also tend to have high δ^{15}N. The reason for this correlation may due to small-scale environmental or agricultural variations being reflected in the faunal isotope ratios. For example, increasing aridity may correlate with increased manuring, which could increase both δ^{13}C and δ^{15}N. Recall that across the entire study region pigs tended to be slightly but significantly higher in δ^{13}C (effect size $0.14 - 0.16$‰, $p = 0.04$) and δ^{15}N (effect size $1.1 - 1.2$‰, $p < 0.0001$) compared to sheep/goat and cattle. These small isotopic differences may reflect differences in management strategies for pigs. The higher δ^{15}N may be related to a tendency for pigs to consume a more omnivorous diet. The overall statistical correlation observed for faunal δ^{13}C and δ^{15}N in Italy may partly reflect these underlying inter-species differences.

7.3.3 Confounding factors: Different diet, same isotopic ratio?

Part of the problem in creating dietary reconstructions based on δ^{13}C and δ^{15}N is that significantly different diets could have identical isotopic ratios. Here, I examine whether it is possible that Roman and Early Medieval diets could have been substantially different, containing significantly different proportions of animal protein, while having the same isotopic ratio.

In 7.1.1 above I estimated the dietary animal fraction based on δ^{13}C and δ^{15}N for Romans at coastal and inland sites. In the initial calculation, the differences in the raw isotopic ratios suggested hugely different (and unrealistically high) quantities of animal products consumed for coastal compared to

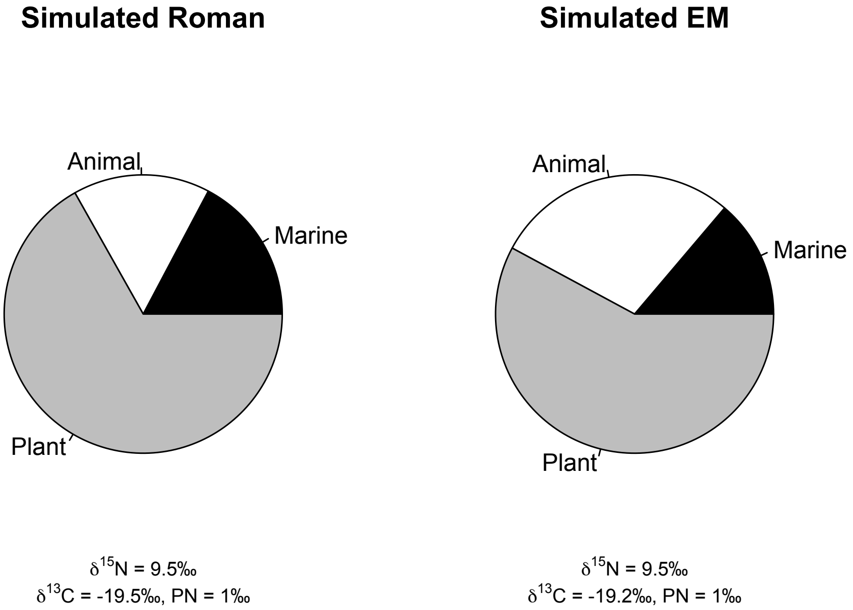

Figure 7.12: *Hypothetical model of the relative contribution of Plant, Marine and Terrestrial Animal protein to the diet of a 'Roman' and 'Early Medieval' individual, based on the models from Figure 7.2 . Here* $\delta^{15}N$ *was assumed to remain the same, while* $\delta^{13}C$ *was* 0.3‰ *different, similar to the effect size observed in the overall European meta-analysis. All models assume* $\delta^{15}N_A = 4.6$, $\delta^{13}C_A = -20.7$, $T_C = 0.5$, *and* $P_N = 1$.

inland sites. Taking the potential consumption of fish into account, the calculation estimated more similar (and realistic) amounts of animal products in the diet. Here I use the same calculations, but apply them to hypothetical Roman and Early Medieval collagen isotope ratios. Based on slight differences between Roman and Early Medieval individuals, the calculations show that when the effect of marine protein consumption is considered, the estimated animal protein fraction in the diet could have been much higher in the Early Medieval period than the Roman period, while keeping δ^{15}N constant.

In Chapter 6, the effect size for Roman to Early Medieval isotopic differences in humans was 0.32‰ for δ^{13}C and 0.51‰ for δ^{15}N.[9] I estimated the

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[9] The difference in human δ^{15}N may be due to a difference in faunal δ^{15}N through time, as discussed in 7.3.2 above. EM faunal δ^{15}N tended to be lower than Roman faunal δ^{15}N, with an estimated effect size of 0.76‰. Here, I calculate whether it is possible a slightly lower EM human δ^{15}N and δ^{13}C could still be consistent with an increase in animal protein consumption relative to the Roman period, independently of baseline faunal changes. Incorporating a

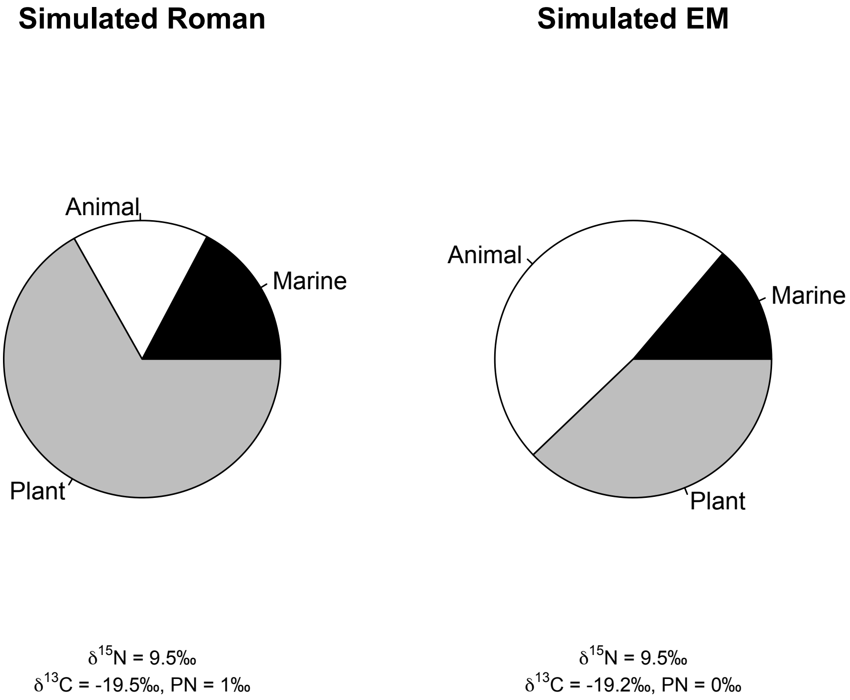

Figure 7.13: *Hypothetical model of the relative contribution of Plant, Marine and Terrestrial Animal protein to the diet of a 'Roman' and 'Early Medieval' individual, based on the models from Figure 7.2 . Here $\delta^{15}N$ was assumed to remain the same, while $\delta^{13}C$ was 0.3‰ lower for the hypothetical EM individual, similar to the effect size observed in the overall European meta-analysis. All models assume $\delta^{15}N_A = 4.6$, $\delta^{13}C_A = -20.7$, and T_C = 0.5. Effects due to differences in manuring strategies are considered: $P_N = 1$ for Roman and 0 for EM.*

animal fraction of the diet, but considered the effect of differences in marine protein consumption, as for 7.1.1 above. While holding δ^{15}N constant at 9.5‰, small changes in δ^{13}C (here I used a difference of 0.3‰ similar to the observed effect size of for R-EM) could have a significant impact on the estimated animal protein fraction of the diet. In this case (Figure 7.12) the dietary animal fraction changed from 16% for the hypothetical Roman to 39% for the hypothetical Early Medieval individual.

We can also account for differences in δ^{15}N at the base of the food chain due to changes in manuring strategies by changing the P_N estimate from 1‰ for the Roman period to 0‰ for the Early Medieval calculation. This 1‰

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baseline change through time would only exaggerate the effect I illustrate here.

difference further exaggerates the potential differences in animal protein consumption while keeping human δ^{15}N constant (see Figure 7.13). The animal protein fraction for the hypothetical Roman is the same as above, but for the Early Medieval person, they increase to a potential 48%. These calculations do not consider the possible confounding effects of additional dietary sources that could introduce further variability in δ^{15}N, such as legumes and freshwater fish. These calculations are not intended to represent actual dietary regimes, but simply to test what is mathematically possible. The calculations suggest that δ^{15}N can remain constant under a variety of dietary regimes, and that the data here is not necessarily inconsistent with the model of diet change at the end of the Roman Empire.

7.3.4 Re-examining the economic evidence

In section 7.1.2 above, I suggested that the isotopic evidence for Roman diet in Italy is not consistent with the picture of a grain-based diet and economy. At face value, the human and faunal isotopic data for central Italy and the whole of Europe do not suggest that there was a significant increase in meat consumption in the post-Roman period. The most parsimonious explanation may be that the Roman and Early Medieval economies and diets were more similar than originally suggested.

The discussion of Mediterranean isotopic ratios above has highlighted that significant geographic and climatic variations exist within this region. There are differences across the Mediterranean, and the varied topography means than even within a relatively small area variations may be extreme. Arthur (2004) and Horden and Purcell (2000) describe the extreme variations in the Italian landscape, and emphasize the very local nature of the agricultural solutions that the population could have adopted as a response. Peasants, be they Roman, Goth, Lombard, Frank or Norman, would have had the same set of local circumstances to adapt to, regardless of larger-scale changes in population density, or urban markets. This is echoed by Spurr (1986) who challenges the notion that Roman agriculture in the late Republic and early Empire was based on cash cropping of grapes and olives.

An area of the lower Liri valley, between Castro dei Volsci and the sites presented in Chapter 5 was the focus of an archaeological survey (Wightman and Hayes, 1994). The study suggested that the topographic variation within the region meant that monoculture for urban markets would not have been practised except for the specialization only possible on the largest estates. The self-sufficient domestic mode of production hypothesized to have taken over after the collapse of Roman markets in the Early Medieval period would have been dominant throughout the Imperial period. Mixed farming of arable land, pasture, vineyards and olive orchards may have been common throughout the period in question. Although a deforested, warm southern Italy under the Roman period is not the ideal habitat for raising pigs, documentary evidence shows the region that is now Lazio and Campagna was expected to provide pigs to Rome under the tax reforms of Diocletian (Wightman, 1994). Mixed farming is also desirable in the Mediterranean because the workload is spread more evenly throughout the year, meaning that slaves can be profitably employed full-time (Spurr, 1986).

Part of the argument for increasing meat consumption in the Early Medieval period relies on an inverse relationship between human population density and animal population density and assumes that humans and animals would have competed for food. If all the land was suitable for growing crops, feeding those crops to animals is an expensive way of achieving the same caloric or protein yield. When populations rise, meat consumption would decline, and when populations fall, meat consumption would increase, as suggested for Dark Age Greece (Snodgrass, 1987), and hypothesized by several authors for the early Middle Ages (Christie, 2004, 2006; Duby, 1974; Hodges, 1982, 1997; Montanari, 1988, 1994, 1999b; Pearson, 1997). But not all land is suitable for growing crops, especially in the mountainous regions of Mediterranean. In reality animal husbandry could have taken a variety of forms, adapting to local geographic and economic circumstances as necessary and allowing for the exploitation of poor soils, slopes, mountainous areas and forests that would otherwise produce poor nutritional yields for humans (Horden and Purcell, 2000). Increasing animal husbandry is only one of many possible responses to intensification (Horden and Purcell, 2000). There is an advantage in being able to trade sheep for wheat that would have made it a desirable option in all periods. Diversifying resource production is necessary to avoid risk. Horden and Purcell (2000) see the Mediterranean economy as so complex and locally-diversified that all periods experienced the kind of self-sufficiency that Montanari and others would apply to the early Middle Ages alone. The isotopic data presented here are consistent with this view of a more complex Mediterranean economy in all periods.

7.4 Late Medieval Dietary Trends

The scope of this study also allows an examination of the dietary changes that may have occurred between the Early Medieval and the Late Medieval period. This period saw a revival of trade, renewed urbanization and the introduction of new foods from the Middle East. In Chapter 6 I noted that the isotopic differences between the Early Medieval and Late Medieval periods tended to be larger than the Roman-EM transition. On a European scale, the meta-analysis suggested a significant effect for EM-LM in terms of δ^{13}C (effect size 0.51‰ $p < 0.0001$) and δ^{15}N (effect size 0.74‰, $p < 0.0001$), although when regions were analysed separately, the significance of these trends was diminished. In the Late Medieval period sites with high δ^{15}N tend to be important urban centres like Rome (Palazzo della Cancelleria, Salamon et al., 2008), Florence, Naples (Fornaciari, 2008), and York (Müldner and Richards, 2007a).

In the Mediterranean alone, Late Medieval humans have significantly higher δ^{13}C compared to earlier periods. The effect size for Mediterranean humans EM-LM is 0.78‰, $p = 0.0034$, while there is virtually no difference in human

δ^{13}C for the Mediterranean between Roman and Early Medieval individuals (see 6.10). For fauna, there were no significant isotopic differences between periods for the Mediterranean on its own, due largely to the small faunal sample sizes, although it was noted that fauna from Late Medieval Spanish sites tended to have high δ^{13}C. The potential confounding influence of geography and climate was discussed above (see 7.3.1). The limited evidence from human-animal Δ^{13}C differences discussed in Chapter 6 did not provide any indication that Late Medieval Mediterranean humans had higher δ^{13}C than expected, relative to the faunal baseline. However, an increase in δ^{13}C through time was observed on a local scale in central Italy (see 7.3.1). In Chapter 2 I discussed how the re-opening of trade in the Late Medieval period brought new foods into Europe. One of these new foods was sorghum, a C4 plant with higher δ^{13}C than the C3 plants that made up most of the edible grains in Europe and the Mediterranean (with the exception of millet). It is possible that this small difference in δ^{13}C in the late Medieval period could reflect small changes in the use of C4 plants such as sorghum or millet.

In Figure 7.8 above, there was a slight increase in δ^{13}C in humans between the Roman period and Late Medieval period, while δ^{15}N remained unchanged. This could relate to a slight increase in the consumption of C4 plants such as millet or sorghum, either directly, or indirectly through animal fodder.[10] One cow from Late Medieval Villamagna had a δ^{13}C ratio of $-18.41‰$, which is significantly higher than the average δ^{13}C from Villamagna ($-20.5 \pm 0.6‰$) and is consistent with a small C4 contribution in the diet. For humans, an increasing substitution of fish for meat in the Late Medieval period (as described in Chapter 2) may also play a role in increasing δ^{13}C in the Late Medieval period. At the Late Medieval monastery/village site of Villamagna in central Italy, individuals buried in association with the ‘Monastery’ part of the

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[10] Sugarcane (another C4 plant) is known to have been introduced to Europe from the Middle East in the Middle Ages (Watson, 1974), however it was a high-status food, and contains no protein, and therefore is unlikely to have had a significant effect on collagen δ^{13}C.

cemetery tend to have slightly higher δ^{15}N compared to other parts of the site, especially for those individuals buried on a N–S axis. This part of the site also has several outliers with relatively high δ^{13}C (−18.9 to −18.4‰). The isotopic data, combined with the contextual information about the burials in a monastic context, suggests an interpretation of an association between religion and fish consumption in the Late Medieval period is possible for central Italy.

7.5 Diet and social status AD 1–1500: Sex and the Cities

In Chapter 5, I noted that there were slight isotopic differences between adults and juveniles at the Italian Late Medieval site of Villamagna. The differences suggested that, compared to juveniles, adults consumed more foods with higher δ^{13}C and δ^{15}N, such as meat and fish. It is possible that such differences in δ^{15}N reflect the metabolic effect of growth in children (Millard, 2000), however models of nitrogen balance during growth in animals (Ponsard and Averbuch, 1999) and measurements of collagen δ^{15}N on growing bone (Waters-Rist and Katzenberg, 2010) suggest such an effect would be minimal. In addition, the fact that both δ^{13}C and δ^{15}N are affected suggest that there is an underlying dietary difference. Foods that are high in δ^{13}C and δ^{15}N tend to be higher status, and it is tempting to infer diet-related status differences between adults and juveniles at Villamagna. A similar pattern was not observed across Europe as a whole, however, where the meta-analysis revealed no significant differences between adults and juveniles.

At Villamagna there were also slightly significant differences based on sex, with males having higher δ^{13}C and δ^{15}N. The estimated effect for δ^{13}C was 0.24‰ ($p = 0.002$) but the effect for δ^{15}N was not significant (0.38‰, $p = 0.10$). Sex-based differences were also examined in the European meta-analysis, where similar differences were observed (δ^{13}C effect size of 0.13‰, $p < 0.0001$; δ^{15}N effect size of 0.32‰, $p < 0.0001$). These differences are small, but they

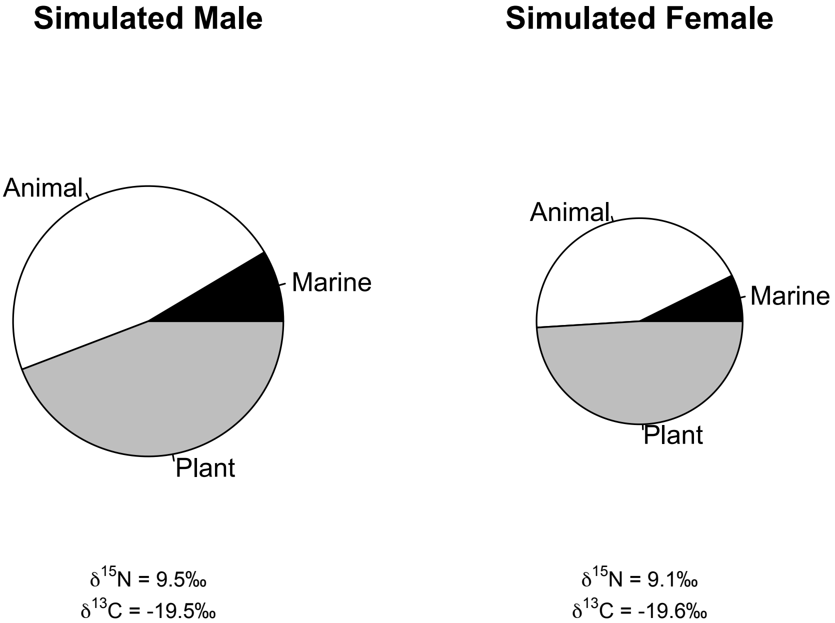

Figure 7.14: *Hypothetical reconstruction of male-female dietary differences, based on the models from 7.2. Here $\delta^{15}N$ for males was assumed to be* 0.4‰ *higher than for females, and male $\delta^{13}C$ was assumed to be* 0.1‰ *higher than for females. All models assume $\delta^{15}N_A = 4.6$, $\delta^{13}C_A = -20.7$, $T_C = 0.5$, and $P_N = 1$. Note that a* 60% *overall required energy intake difference between males and females is also suggested by drawing the chart for females with* 60% *of the area of the chart for males*

are statistically significant and are the result of a model that controlled for interference due to location, period, proximity to the coast and random inter-site variation. Since pregnancy is a state of growth, it is possible that sex-based differences could be due to a metabolic effect on δ^{15}N confined to females (Fuller et al., 2004, 2006b). However, analysis of females of known parity history and modelling of collagen turnover rates suggests that the effect of pregnancy is minimal (Nitsch et al., 2010).

It is therefore likely that the slight isotopic differences reflect genuine dietary differences between males and females, albeit small ones. In Figure 7.14 I re-use the same models from Figure 7.12 above, but calculate the effect of 0.1‰ difference in δ^{13}C and a 0.4‰ difference in δ^{15}N. In the example in Figure 7.14, there is only about a 5% difference in the estimated animal fraction of the diet. However, by varying the size of the diagram for males and females this figure also illustrates that the absolute amount of meat consumed may have been different. If females had only 60% of the energy and protein needs of males, and there was a 5% difference in the relative percentages of animal vs. plant protein consumed, it would amount to the female meat portion being consistently half the size of the male meat portion.

In Table 6.11 I showed that the difference between male and female diets may have changed over time. The effect size was greatest for the Late Medieval period (0.20‰ for δ^{13}C and 0.51‰ for δ^{15}N, $p < 0.0001$ for both), while there was virtually no difference between males and females in the Early Medieval period (δ^{13}C effect size 0.04‰, $p = 0.24$; δ^{15}N effect size 0.13‰, $p = 0.06$). In Chapter 2 I discussed a wide variety of factors that could give rise to male-female dietary differences. These differences could be related to deliberate status choices: Roman writers recommended restricting food for young women (Garnsey, 1999) and women in the Medieval period were driven to fasting as a means of religious expression (Bynum, 1987). In addition, Reitsema et al. (2010) point out that male–female dietary differences also frequently result from sex-based labour divisions, with men and women occupying different spaces and having access to different types of food. It is possible that the change in male–female dietary differences over time reflect such divisions of labour. The economic complexity of the Roman and Late Medieval periods created opportunities for earning outside the home, especially in cities and through trade. The more self-sufficient Early Medieval economy may have resulted in men and women living closer together, participating in similar economic activities, and eating similar kinds of food. When coastal and inland sites are modelled separately, the sex-based effect for δ^{15}N remains the same for coastal and inland individuals, but the size of the difference for δ^{13}C between males and females reduces to 0.08‰ ($p = 0.11$) for individuals from Coastal sites (see Table 7.1). This suggests that, to the extent that the difference in δ^{13}C between males and females is related to differences in marine food consumption, these differences are minimal when geography makes such foods abundant, but exaggerated in inland areas where such foods may be more rare.

Table 7.1: *Statistics for mixed effects model fitted by REML for adult humans, calculated for coastal and inland sites separately.*

Coastal sites

862 Observations, 37 Groups. AIC= 1639 (δ^{13}C), 2734 (δ^{15}N) . Random effect = 'Site'

Fixed Effects:

Date		δ^{13}C diff	p	δ^{15}N diff	p
Compared to EM	LM	0.88	< 0.0001	-0.25	0.38
	Roman	0.15	0.68	-0.57	0.28
Compared to Roman	LM	0.72	0.03	0.32	0.48
Location					
Compared to Med	NE	-1.45	0.0008	0.51	0.34
	England	-1.13	0.0067	0.62	0.25
Compared to NE	England	0.32	0.53	0.11	0.87
Male/female					
Compared to Female	Male	0.08	0.11	0.34	0.0003

Inland sites

1834 Observations, 63 Groups. AIC= 2936 (δ^{13}C), 5328 (δ^{15}N) . Random effect = Site

Fixed Effects:

Date	δ^{13}C diff	p	δ^{15}N diff	p	
Compared to EM	LM	0.35	< 0.0001	1.09	< 0.0001
	Roman	0.26	0.0031	0.77	< 0.0001
Compared to Roman	LM	0.09	0.26	0.32	0.0420
Location					
Compared to Med	NE	-0.86	< 0.0001	1.23	0.01
	England	-0.68	< 0.0001	1.11	0.0026
	CE	-0.44	0.04	0.23	0.67
Compared to CE	NE	-0.42	0.09	1.00	0.1
	England	-0.24	0.25	0.88	0.1
Compared to NE	England	0.18	0.33	-0.12	0.79
Male/female					
Compared to Female	Male	0.16	< 0.0001	0.31	< 0.0001

The unique role that cities play in dietary strategies has been a constant theme in this research. The decline and rebirth of cities during the period of study is the key signifier of the wider political, social and economic trends that occurred from the height of the Roman Empire to the beginning of the Renaissance. The question of examining dietary changes at the Roman to Early

Medieval transition is therefore at least partially concerned with how urbanization affects resource production and distribution, and how these practices affect stable isotope ratios.

I noted throughout this study that individuals living in cities tend to have high δ^{15}N, especially in Roman Italy where there was good archaeological evidence on which to assess degrees of urbanization. This may partly reflect a social phenomenon. Cities represented concentrations of wealth, and the elite who lived there may have chosen to consume a diet of primarily high δ^{15}N foods as befitted their status. In addition, the high δ^{15}N in cities partly reflects the strategies that are employed to maximize food production, which tend to increase δ^{15}N. Manuring is an intensive agricultural strategy which could increase the carrying capacity of the land, while increasing baseline δ^{15}N. But when complex societies reach the carrying capacity of their land, higher population densities can only be sustained by exploiting non-terrestrial sources of food. If these are marine- or freshwater-based, they could result in a further increase in δ^{15}N in humans above the animal baseline. Such a strategy has been used to explain the increasing presence of shell-middens along the coast of Hampshire and Sussex in the 8th and 9th centuries, where populations faced with an over-extended agricultural system were forced to exploit these additional protein sources (Hodges, 1982). The isotopic evidence presented here suggests that throughout Europe and the Mediterranean, from the Roman period to the Late Medieval period, similar adaptations occurred, in response to shifts in local economic circumstances. It should be emphasized that considerable dietary variation between sites prevents making strong conclusions about long-term dietary trends.

che cos'è la gloria di Dante appresso a quella degli spaghetti?
—Giuseppe Prezzolini, 1954, *Maccheroni & C.*

8

Summary and Conclusions

8.1 From Bread to Bratwurst?

The primary goal of this thesis was to use evidence from stable isotope analysis to determine whether there was a significant change in diet in Europe between the Roman and Medieval periods. The historical and archaeological evidence suggested that food practices might have changed as a result of the social, economic and political changes that occurred in Europe from the 1st to the 15th century AD. Within Italy specifically it was hypothesized that a highly-integrated, cereal-based Roman economy was replaced by a localized, mixed sylvo-pastoralist economy in the Early Medieval period. This also coincided with the movement of central European populations into Italy, and with the rise of Christianity, all of which may have contributed to a situation where meat was more highly valued, and more readily available. Stable isotope analysis was a useful to tool to test this hypothesis, because it provided a direct, comparable assessment of relative amounts of animal protein versus plant or marine protein in the diet. In Chapter 1, I explained how this study was designed to test isotopic differences in Roman and Medieval humans on a local scale (Central

Italy) and on a continental scale, with a meta-analysis of European data.

A closer examination of the historical and archaeological evidence (Chapter 2) suggested that multiple dietary scenarios may have occurred. There was evidence from pottery and agricultural reconstructions that the Roman economy in Italy may not have been uniformly focused on the output of grain. Zooarchaeology and historical evidence suggested pig was widely consumed, especially in urban areas. Overland transport in the Roman empire may have impeded trade in the interior. Despite the emphasis on grain consumption in classical texts and scholarship, it is clear that the argument for locally-focused mixed animal husbandry (and accompanying meat consumption) is not without merit.

In Chapter 3, I introduced the added complication of uncertainty in the isotopic analysis. Current understanding of human–animal trophic level relationships is imperfect. Climatic and geographic factors influence stable isotope ratios and must be accounted for. Low-protein diets may result in a decrease in the direct routing of carbon to collagen, and thus obscure the signal of dietary protein.

I attempted to overcome some of these historical and methodological problems in my selection of sites (Chapter 4). I undertook new analyses of sites in central Italy designed to complement the types of sites that had been previously studied. Prior to this study, our understanding of Roman and Medieval Italian diet was largely based on isotopic evidence from coastal, urban sites. The picture has been improved by the analysis of new sites from inland, rural areas. I also designed and carried out a meta-analysis of all available previously published data from Europe and the Mediterranean c. AD 1–1500. This meta-analysis was structured to take into account geographic effects by recording the latitude, longitude and altitude of the site, as well as its proximity to the coast. Additional factors were examined, including date, location, and the sex and age of the individuals.

My analysis of the new Italian data (Chapter 5) and the meta-analysis of previously published data (Chapter 6) required the application of statistical tools that had not been previously used in palaeodietary isotopic studies. Mixed multi-level models were used because they account for the statistical uncertainty from inter-site random variation. Then, multiple explanatory factors can be added and examined. Any multi-site comparison that does not use such a model will risk over-estimating the significance of these explanatory factors. Within Italy (Chapter 5) I employed a scaled-down version of this model, but the small sample sizes led to few significant trends. Coastal/Inland differences were significant predictors of Italian δ^{13}C but not δ^{15}N. When I replaced Coastal/Inland with a binary definition of Urban/Rural (based on *a priori* assumptions and not necessarily systematic or unbiased), I was able to explain much more of the variation in Italian δ^{13}C and δ^{15}N. In the meta-analysis of European data (Chapter 6), I showed how such a model could be used to detect regional differences in faunal δ^{13}C (with the Mediterranean being slightly higher than other regions). There were also slight differences in faunal isotopic ratios through time, with the Early Medieval period having slightly lower δ^{15}N. There was a similar, and more significant effect for humans through time. Humans in the Early Medieval period had significantly lower δ^{13}C and δ^{15}N compared to other periods. Other factors such as sex, and location played a role as well.

The original hypothesis, that meat consumption increased in Early Medieval Italy and Europe, could not be supported based on a simple interpretation of the available evidence. However, in Chapter 7 I discussed several complicating factors. First, it was possible that the Roman and Early Medieval diets may have been more similar than originally hypothesized. The standard isotopic model overestimates the animal fraction in the diet because δ^{15}N for many individuals in Roman Italy was significantly higher than the faunal baseline. I created a model to estimate the fraction of animal protein in the diet, by correcting for uncertainties in the Δ^{15}N trophic level enrichment factor and differences in cereal–fodder δ^{15}N, after Hedges and Reynard (2007). I also added a parameter to account for marine protein consumption based on a linear relationship with δ^{13}C. This calculation resulted in a lower and more realistic animal protein fraction estimation for the entire population. This estimation was, however, higher than was expected given the historical and archaeological model of a grain-based Roman diet and economy.

There were also complications in interpreting the isotopic differences and similarities across time. Some of the chronological variation in human δ^{15}N followed the pattern in the faunal baseline. The large isotopic differences across the Mediterranean likely reflected climatic differences, making it difficult to compare results across this large region. The cooling and increased precipitation that Europe experienced c. AD 400–800 could have resulted in baseline isotopic changes. In addition, a less intensive agricultural strategy with decreased levels of manuring at the start of the Early Medieval period could have lowered soil δ^{15}N. A small effect at the base of the foodchain could create a large difference in human isotopic ratios, and affect the interpretation of the results. Domesticated herbivore isotopic ratios were examined as a potential control, but the available sample sizes across the study area were small compared to the number of humans. A future study of European dietary trends at this time would benefit from a closer examination of potential baseline isotopic fluctuations.

Even assuming there were no significant changes in the isotopic baseline through time, there are multiple plausible dietary reconstructions based on similar δ^{13}C and δ^{15}N. In 7.3.3 I showed that small changes in marine fish consumption could result in dramatically different estimates of the amount of terrestrial animal protein in the diet. If changes in manuring practices are also considered, the effect could have been even greater. Thus, the isotopic data is not necessarily inconsistent with a diet change at the end of the Roman empire. A largely grain-based diet, supplemented with equal amounts of animal and marine protein, could have been replaced by a diet with double the animal protein fraction, keeping δ^{15}N unchanged, and δ^{13}C nearly unchanged.

Changing social patterns through time may also have affected diet and stable isotope ratios. In Chapter 7 I highlighted the isotopic trends from which one could infer social behaviour. Sex-based dietary differences seem to have been almost non-existent in the Early Medieval period, and much greater in the Roman and Late Medieval periods. I suggested this may be the result of differences in the division of labour through time, and may be one of the few pieces of evidence from this study that directly supports the notion of a small-scale localized economy in the early Middle Ages. At other periods, there were more economic opportunities outside the home, especially in cities. Male and female diets may have diverged as a result of men and women being employed in different kinds of labour, and having access to different foods. The isotopic effects and dietary inferences observed here are partly related to the growth, decline and rebirth of cities that occurred c. AD 1 to 1500. Nitrogen isotope ratios tended to be higher in cities, partly due to the presence of elites, but partly due to the economic and agricultural strategies that humans tend to adopt in order to sustain high population densities.

Interpreting the isotopic results of this study in light of all these potential confounding factors does not make it necessary to reject the initial hypothesis that meat consumption increased in the Early Medieval period. However, there is also good archaeological and historical evidence to support the counter-argument, that the Roman and Early Medieval periods were more similar in terms of economy, agriculture and diet than originally supposed. Farming practices under the Roman empire were fluid, still subject to local conditions and limitations (Spurr, 1986). Modern historians may underestimate the uncertainties of agricultural life in the pre-modern world. The physical limits of transportation in the ancient world were enormous compared to today. Crop failures, disease and warfare were part of the living memory of the farmers who, despite the lure of a profitable urban market, would have kept pigs, sheep or goats along with their crops, trees and vines. True monoculture is only possible in our modern integrated global food system with fast, cheap, transportation and effective means of preservation. While there may have been small changes in food production and consumption patterns between AD 1 and 1500, they do not seem to have had a large effect on stable isotope ratios. This is because the isotopic data is a blurred average of what must have been a highly variable system. Had the changes been uniform, widespread and abrupt (which is the impression one is often left with from historians' accounts) such a difference should have been detectable isotopically. Instead, it seems that local needs would have always taken precedence over the wider market forces, to varying degrees.

There remain significant areas of uncertainty in the field of isotopic palaeodietary study. The interpretation of the results presented here was limited by the same problems of variability and equifinality that have raised concerns for decades. While this thesis has attempted to address these problems through an analysis of a large amount of data, new methodological developments may prove fruitful for future research in Roman and Medieval diet.

8.2 Future Work

- **Improved sampling of faunal specimens:** The statistical significance of the models presented in Chapter 6 was largely dependent on the number of individuals analysed. There were relatively few domesticated herbivore specimens available for the meta-analysis compared to humans, and as a result there were few significant trends in faunal variation across Europe. In order to truly compare human and faunal isotopic variation through time, larger faunal sample sizes would be needed. Faunal isotopic ratios could be used to examine questions related to land-use and agricultural practices. One significant observation of this study has been the extent of isotopic variability within the Mediterranean. In Chapter 7 I suggested this is the result of both large-scale and small-scale geographic and climatic variation. This small-scale variability could be exploited by future studies to examine issues of archaeological and historic importance. One potential application is the examination of the nature and extent of transhumance in classical antiquity. Isotopic analysis of animal tooth sequences may reveal serial variation and provide evidence for the movement of animals through the year.

- **Archaeobotanical and Single Amino Acid δ^{13}C studies:** In Chapter 7 I noted the problem of interpreting δ^{15}N in humans relative to fauna. For inland Roman Italian sites, human δ^{15}N was high enough to suggest a diet containing a significant proportion of animal protein relative to plant protein. These results have the potential to alter the picture of a largely grain-based Roman diet, but other possibilities exist. First, the consumption of freshwater fish and its possible effect of increasing δ^{15}N in humans relative to fauna remains an ongoing problem. Second, manuring may alter the baseline δ^{15}N in plants consumed by humans differently from δ^{15}N in animal fodder. Although we can calculate the effect of manuring and freshwater fish consumption on human δ^{15}N, we have no data with which to measure such an effect. Any future investigation into the nature of Roman rural diet should attempt to provide an independent measure of manuring and freshwater fish consumption, which could address the problem of equifinality noted above. Fortunately there have been recent developments made in both these areas, with the isotopic analysis of archaeobotanical remains to detect manuring (Fraser et al., 2011) and the ability of single amino acid δ^{13}C analysis to discriminate between freshwater, marine and terrestrial diets (e.g. Corr et al., 2009; Naito et al., 2010).
- **Evaluating dietary differences between Romans and non-Romans:** At present, isotopic studies comparing adjacent Roman and non-Roman populations do not exist. Although it was originally hoped that the meta-analysis would make it possible to make comparisons of contemporary populations across both sides of the Roman frontier, the available

data did not make this feasible. This is an area where future research could be applied to better understand the nature of Roman/non-Roman interactions in antiquity. In addition, a better selection of more representative Lombard and non-Lombard sites may have provided a better dietary comparison within Italy. Future palaeodietary research in Italy may wish to focus on humans from typically Lombard sites, such as Vicenne-Campochiaro, in central Italy.

- **Improving chronological control and examining climate change:** The division of the study into three chronological units (Roman, Early Medieval and Late Medieval) had sound historical basis, but it was an artificial division. It was a simplification of a complex political period. Future studies may be able to treat time as a quantitative rather than categorical variable, by converting archaeological phase information (e.g. 'late 3rd century AD', '10th-12th century') into absolute calendar dates. The lack of chronological resolution meant it was impossible to attempt a detailed investigation into human-climate interactions. Recent palaeoclimate studies have improved our understanding of climate change in the last 2500 years (Büntgen et al., 2011). With the changes in temperature and precipitation through time established, it becomes possible to examine human adaptations to these fluctuations. A fine-resolution study comparing local isotopic changes in humans and animals relative to independent palaeoclimatic records would improve our understanding of human-climate interactions during this complex period.
- **Examining archaeological factors related to urbanization more systematically:** In Chapter 5 and 7 I discussed how urban sites tend to have higher δ^{15}N than rural sites. I suggested both social and economic reasons why this might be the case. This observation would benefit from a more critical examination, incorporating a more systematic assessment of relative degrees of urbanization based on archaeological criteria into the isotopic meta-analysis.

8.3 Conclusions

This study demonstrated the utility of comparing multiple scales of evidence when using stable isotope data to make dietary inferences. On a local scale, I showed how comparisons that do not consider the nature of the site (coastal/inland, rural/urban) may give a false impression of dietary changes through time. On a continental scale, I demonstrated how multiple dimensions of data can be incorporated alongside isotopic data using statistical models. The crucial element of the model is taking into account site-level random variation. Failure to do so increases the risk of a Type I error, and in the context of this European meta-analysis would have resulted in observing apparently significant trends where none actually exists. In Chapter 7 I presented a way to estimate the animal fraction of the diet by taking into account the potential for marine fish consumption. There has long been an awareness of the multiple confounding factors that affect dietary interpretations from stable isotope ratios. Rather than simply list these factors, I hope that this study has taken some step towards accounting for confounding influences quantitatively.

It is tempting to view the fall of the Roman Empire as the most significant event in European history c. AD 1 to 1500: a deep wound which took centuries to heal. The political and social changes that resulted were thought to have had a significant effect on diet, with animal meat being more widely consumed during the Early Medieval period. This study examined the isotopic evidence for changing food behaviour at this time on two scales. On a local level, within a single valley in central Italy, there were no changes in δ^{15}N through time to suggest meat consumption changed. On a European level, there was also no evidence for increasing δ^{15}N in the Early Medieval period. The overall trend, dominated largely by England, was of decreasing δ^{15}N c. AD 500–1000. Throughout Europe, the isotopic changes that occurred c. AD 1000 were greater than those that occurred c. AD 500. This suggests that the growth of cities and expansion of population in the Late Medieval period potentially had a greater effect on food practices than the fall of the Roman Empire. Politically, economically and socially, Rome's collapse was an apparently a traumatic event, but it did not leave the expected isotopic dietary scar.

Appendices

A

Data tables and summaries from previously published studies

A.1 Casale del Dolce

Table A.1: *Results from Casale del Dolce*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1	rib	CTC 1	A	5.32	-20.56	0.29	6.49	0.04	3.34	33.98	11.85
2	rib	CTC 2	A	5.47	-19.84	0.07	7.79	0.26	3.26	40.62	14.54
3	rib	CTC 3	A	5.33	-20.01	0.17	8.45	0.2	3.3	40.73	14.43
4	rib	CTC 4	A	7.76	-19.92	0.15	8.82	0.05	3.3	42.29	14.94
6	rib	CTC 6	A	7	-20.15	0.07	7.7	0.11	3.27	42.13	15.04
7	rib	CTC 7	A	6.94	-20.62	0.04	7.93	0.09	3.35	42.27	14.74
8	rib	CTC 8	A	11.22	-20.13	0.08	8.3	0.17	3.2	42.48	15.51
9	rib	CTC 9	A	5.44	-20.45	0.06	7.4	0.02	3.35	42.99	14.98
11	rib	CTC 11	A	10	-20.36	0.04	7.7	0.1	3.28	44.49	15.85
16	rib	CTC 16	A	7.8	-20.1	0.14	8.07	0.12	3.34	44.9	15.69
18	rib	CTC 18	A	3.95	-19.99	0.18	7.57	0.09	3.25	35.38	12.69
19	rib	CTC c. 19	A	12.62	-20.4	0.09	6.49	0.28	3.33	43.37	15.2
20	rib	CTC 20	A	7.5	-20.1	0.12	7.29	0.41	3.3	45.26	15.98
21	rib	CTC 21	A	13.33	-19.9	0.12	8.74	0.26	3.26	44.69	15.99
24	rib	CTC 24	A	8.91	-19.2	0.08	10.93	0.12	3.33	43.75	15.35
25	rib	CTC 25	A	7.89	-20.01	0.23	8.15	0.24	3.35	27.23	9.47
27	rib	CTC 27	A	10	-20.21	0.05	6.87	0.06	3.24	42.5	15.32
28	rib	CTC 28	A	4.83	-20.08	0.07	7.72	0.17	3.32	42.03	14.75
29	rib	CTC 29	A	4.65	-20.33	0.12	6.44	0.2	3.29	38.16	13.53
30	rib	CTC 30	A	13.39	-20.24	0.13	8.15	0.18	3.25	42.11	15.14
31[b]	rib	CTC 31	A	1.38	-20.38	0.04	8	0.35	3.64	40.01	12.86
34	rib	CTC 34	A	11.46	-19.94	0.07	7.84	0.42	3.29	38.8	13.77

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

Continued on next page

Table A.1 – continued from previous page

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
35	rib	CTC 35	A	14.78	-19.95	0.03	7.75	0.07	3.24	41.12	14.8
37	rib	CTC 37	A	5.95	-20.64	0.02	7.07	0.13	3.27	43.52	15.5
38	rib	CTC 38	A	9.88	-20.08	0.08	7.79	0.1	3.26	40.5	14.5
39	rib	CTC 39 A	A	6.22	-19.38	0.05	8.63	0.09	3.29	39.75	14.1
42	rib	CTC 42	A	6.8	-19.22	0.14	10.16	0.13	3.24	43.78	15.74
44	rib	CTC 44	A	8.61	-19.69	0.02	10.14	0.14	3.27	44.07	15.73
45	rib	CTC 45	A	12.08	-20.1	0.07	6.67	0.06	3.27	43.01	15.35
48	rib	CTC 48	A	13.13	-19.81	0.06	11.32	0.15	3.25	43.68	15.7
49	rib	CTC 49	A	12.22	-20.25	0.12	7.36	0.45	3.25	44.64	16.01
50	rib	CTC 50	A	8.8	-20.14	0.1	6.82	0.17	3.28	43.1	15.36
51	rib	CTC 51	A	6.99	-18.83	0.12	11.3	0.19	3.3	40.4	14.31
52	rib	CTC 52	A	10.27	-20.32	0.05	7.56	0.1	3.28	42.15	14.98
53	rib	CTC 53	A	13.38	-20.41	0.1	6.62	0.06	3.29	43.01	15.24
56	rib	CTC 56	A	12.32	-19.47	0.09	10.11	0.05	3.29	40.84	14.51
57	rib	CTC 57	A	7.92	-20.22	0.12	7.98	0.18	3.28	42.24	15.04
58	rib	CTC 58	A	10.5	-19	0.01	12.41	0.09	3.24	44.6	16.08
59	rib	CTC 59	A	8.8	-20.74	0.07	6.43	0.08	3.29	44.06	15.63
60	rib	CTC 60	A	14.86	-19.71	0.07	7.64	0.2	3.23	42.03	15.18
61	rib	CTC 61 B	A	13.41	-20.02	0.05	6.84	0.14	3.18	40.79	14.95
62	rib	CTC 62	A	3.08	-20.09	0.08	7.28	0.1	3.27	41.16	14.68
63	rib	CTC 63	A	12.06	-19.67	0.04	8.31	0.11	3.27	42.45	15.16
64	rib	CTC 64	A	10.83	-20.43	0.08	6.71	0.12	3.25	44.73	16.03
65	rib	CTC 65	A	6.99	-19.94	0.04	7.62	0.13	3.3	39.56	14.01
104	rib	CTC 46 IV A	A	2.86	-20.39	0.03	6.61	0.11	3.33	40.03	14.01
106	rib	CTC 46 VI	I	12.45	-20.31	0.1	7.12	0.42	3.2	44.29	16.15
107	rib	CTC 46 VII	A	6.03	-20.13	0.05	7.72	0.26	3.32	36.7	12.89
109	rib	CTC 46 IX	A	5.25	-19.42	0.06	7.42	0.06	3.29	34.97	12.39
110	rib	CTC 46 X	I	12.11	-20.02	0.02	6.58	0.04	3.2	44.43	16.2
111	rib	CTC 46 XI	A	5.6	-19.57	0.05	7.58	0.08	3.28	36.92	13.14
112	rib	CTC 46 XII	A	5.82	-20.38	0.07	7.6	0.07	3.27	36.67	13.07
114	rib	CTC 46 XIV A	A	5.19	-20.17	0.07	6.64	0.22	3.29	42.66	15.12
115	rib	CTC 46 XV	A	5.11	-20.21	0.06	5.7	0.13	3.33	43.55	15.27
119	rib	CTC 46 XIX A	A	6.73	-20.3	0.04	7.18	0.09	3.22	43	15.58
120	rib	CTC 46 XX.I	I	2.65	-18.22	0.24	15.38	0.75	3.27	41.69	14.91
121	rib	CTC 46 XXI.I	I	4.48	-20.18	0.05	6.38	0.01	3.27	43.1	15.38
122	rib	CTC 46 XII	I	5.95	-20.38	0.09	6.42	0.06	3.28	41.65	14.82
125	rib	CTC 46 XVII A	A	4.89	-20.27	0.03	6.88	0.31	3.23	42.17	15.23
126	rib	CTC 46 XVII B	A	16	-18.55	0.16	11.58	0.35	3.21	42.68	15.52
128	rib	CTC 46 III	A	7.97	-19.38	0.08	8.68	0.18	3.22	41.82	15.16
131	rib	CTC 46 IV B	A	3.6	-20.34	0.55	7.71	0.34	3.38	21.57	7.47
133	rib	CTC 46 US 711 A	A	12.5	-20.39	0.22	6.22	0.72	3.24	43.7	15.73
135	pelvis	CTC 46 VIII A	A	4.21	-19.93	0.1	8.2	0.57	3.3	41.44	14.65
137	rib	CTC 46 VIII C	I	6.75	-19.97	0.1	6.49	0.46	3.28	37.17	13.2
138	rib	CTC 46 IX	I	2.96	-19.09	0.09	9.65	0.46	3.21	41.41	15.04

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.2 Civitanova Marche

Table A.2: *Results from Civitanova Marche*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1	rib	T4/74a	A	3.51	-19.16	0.03	10.73	0.13	3.37	37.11	12.85
2	tibia	T2/74e	A	7.32	-20.19	0.13	8.63	0.21	3.27	38.28	13.64
3	rib	T21/74a	A	6.03	-19.38	0.08	9.41	0.17	3.29	40.78	14.48
4	humerus	T13b	A	10.8	-18.06	0.06	13.48	0.13	3.24	40.9	14.73
5	tibia	T13/74c	A	4.22	-20.15	0.02	8.75	0.04	3.25	41.69	14.96
6	fibula	T6/74c	A	1.31	-20.09	0.06	8.64	0.03	3.31	41.27	14.56
7	humerus	T6/74a	A	7	-19.63	0.03	9.65	0.03	3.18	40.95	15
8	rib	T3/74	A	2.54	-19.28	0.09	10.58	0.25	3.52	28.6	9.48
9	long bone	T19/74 A	A	1.83	-18.16	0.1	11.05	0.09	3.33	40.32	14.13
10	femur	T19/74 C	A	2.73	-19.74	0.06	9.3	0.13	3.5	29.19	9.72
11	rib	T3/77	A	15.49	-19.99	0.03	9.94	0.03	3.19	42.05	15.37
12	rib	T2/77	A	8.99	-19.05	0.09	10.64	0.07	3.25	39.22	14.08
13	ulna	T19f	A	10.26	-20.15	0.06	8.43	0.14	3.15	45.68	16.95
14	fibula	T6b	A	9.35	-19.75	0.09	9.31	0.05	3.21	41.29	15
16	radius	T20b	A	7.64	-19.85	0.05	9.21	0.1	3.22	42.36	15.35
17	femur	T20c	A	4.42	-19.87	0.07	9.55	0.03	3.29	41.62	14.77
18	ulna	T20g	A	3.7	-19.41	0.08	11.3	0.02	3.47	39.52	13.3
19	femur	T20e	A	5.06	-18.97	0.05	7.21	0.09	3.16	41.54	15.35
20	ulna	T20f	A	2.45	-20.25	0.06	8.39	0.05	3.3	40.59	14.35
21	scapula	T6d	A	6.58	-20.02	0.03	8.65	0.17	3.26	38.5	13.8
22	humerus	T6e	A	2.99	-20.09	0.06	8.55	0.08	3.25	40.47	14.51
24	ulna	T14L	A	5.34	-20.03	0.03	8.63	0.04	3.25	39.2	14.07
25	ulna	T14M	A	4.62	-19.69	0.04	8.83	0.19	3.25	42.23	15.18
26	tibia	T14g	A	4.68	-20.05	0.04	8.47	0.19	3.22	41.61	15.06
27	fibula	T14N	A	11.67	-19.82	0.12	9.39	0.23	3.21	41.98	15.27
28	fibula	T23/74f	A	6.96	-19.44	0.06	9.04	0.09	3.14	40.8	15.15
29	femur	T24/74b	A	10.28	-20.13	0.12	9.01	0.35	3.2	40.85	14.87
30	femur	T8 C	A	6.09	-19.73	0.02	9.12	0.09	3.24	40.47	14.58
31	rib	T21/74c	A	11.92	-18.5	0.01	12.21	0.12	3.15	44.71	16.6

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.3 Esanatoglia

Table A.3: *Results from Esanatoglia*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
3	rib	T6b	A	4.2	-19.64	0.08	8.35	0.1	3.29	41.59	14.74
4[b]	clavicle	T7c	A	1.92	-19.65	0.04	7.86	0.52	3.45	30.72	10.4
5	rib	T2	I	9.23	-18.17	0.11	11.43	0.21	3.27	40.43	14.44
6	rib	T1	A	5.17	-19.36	0.05	8.71	0.15	3.33	40.75	14.28
7	rib	T4A	A	498.63	-19.46	0.05	8.62	0.13	3.34	40.53	14.16
8	rib	T3	A	2.92	-19.54	0.06	7.37	0.14	3.26	41.46	14.82
9	rib	T4b	A	9.32	-19.17	0.01	8.14	0.12	3.18	42.31	15.5
10	rib	T5c	A	5.52	-19.33	0.19	8.15	0.24	3.31	40.35	14.2
11[b]	scapula	T6a	A	3.13	-19.4	0.04	7.37	0.26	3.46	33.1	11.18
12	rib	T5b	A	9.47	-19.45	0.02	8.64	0.22	3.25	38.46	13.82
13	rib	T5a	A	4.6	-19.58	0.07	8.92	0.15	3.32	42.49	14.94

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.4 Marcellino e Pietro

Table A.4: *Results from Marcellino e Pietro*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
11	cranium		A	2.41	-18.97	0.03	10.62	0.85	3.25	34.46	12.35
14	cranium		A	11.86	-19.51	0.06	8.91	0.33	3.22	42.34	15.31
16	cranium		A	1.88	-19.1	0.02	10.97	0.51	3.3	37.67	13.34
2	cranium		A	6.72	-18.97	0.1	10.14	0.59	3.24	38.13	13.73
3	cranium		A	3.97	-18.99	0.12	10.84	0.62	3.29	37.7	13.38
4[b]	cranium		A	2.15	-18.74	0.12	10.97	0.27	3.37	25.6	8.88
5	cranium		A	1.9	-19.05	0.07	11.31	0.35	3.28	36.76	13.07
7	cranium		A	10	-19.08	0.01	10.79	0.31	3.22	40.88	14.78
8	cranium		A	15.06	-18.45	0.5	11.25	0.04	3.23	38.8	14.04
11	cranium		A	14.68	-18.67	0.06	12.92	0.34	3.21	42.05	15.29
13[b]	cranium		A	4.67	-19.2	0.02	10.45	0.49	3.19	38.15	13.98
15	cranium		A	11.06	-20.06	0.09	6.97	0.66	3.24	39.09	14.08

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.5 Osteria della Fontana

Table A.5: *Results from Osteria della Fontana*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1[b]	rib	F T2	A	2.69	-19.69	0.02	7.8	0.2	3.35	39.27	13.68
2	rib	T3	A	1.14	-19.42	0.03	5.97	0.63	3.45	35.34	11.96
3	tibia	T38	A	7.17	-20.12	0.08	7.29	0.07	3.21	41.05	14.89
5	rib	T7	A	3.24	-20.08	0.05	7.49	0.66	3.41	33.48	11.45
6	rib	F T1	A	5.84	-19.95	0.02	6.86	0.28	3.26	39.26	14.04
7	rib	T1 (TB1 F60/P.57)	A	5.57	-19.02	0.04	11.58	0.26	3.3	39.95	14.12
8	rib	T5 F60/P.116	A	5.88	-20.02	0.07	7.68	0.27	3.32	33.71	11.83
9	rib	F T5	A	4	-19.58	0.04	6.73	0.35	3.3	40.11	14.17
10	rib	T7 F60/P116	A	8	-20.14	0.08	7.48	0.3	3.3	41.54	14.7
11	rib	T8 T60/P116	A	4.29	-19.53	0.07	8.75	0.17	3.27	40.07	14.32
12[b]	tibia	F- T10	A	3.24	-19.93	0.01	5.73	0.72	3.53	40.01	12.86
13	rib	T6 F.60 P-116	A	9.11	-19.31	0.04	9.14	0.08	3.24	41.89	15.08
14	rib	F- T8	A	7.73	-19.75	0.06	6.44	0.15	3.24	39.99	14.41
16	rib	T4 F60 P.57	A	8.89	-19.54	0.02	8.6	0.14	3.25	42.58	15.29

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.6 Palestrina

Table A.6: *Results from Palestrina*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1	tibia	T.11	A	6.47	-19.65	0.04	8.7	0.12	3.22	42.3	15.34
2	rib	T9	A	4.23	-20.65	0.05	8.67	0.08	3.52	40.46	13.43
3	rib	T10	A	10.51	-19.29	0.13	10.66	0.07	3.28	41.52	14.76
4	rib	T13	A	5.53	-20.2	0.04	8.1	0.19	3.25	40.17	14.43
5	rib	T14	A	11.57	-20.11	0.15	8.38	0.14	3.28	41.99	14.95
6	rib	T7	A	5.25	-19.33	0.06	10.59	0.05	3.24	41.34	14.89
8	rib	T1a	A	11.64	-19.09	0.12	11.51	0.18	3.26	43.33	15.5
9	femur	T7b	A	1.8	-19.66	0.11	9.35	0.32	3.23	40.99	14.82
10	rib	T12	A	11	-19.51	0.06	9.54	0.04	3.18	42.77	15.67

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.7 Pompeii

Table A.7: *Results from Pompeii*

ID	Bone	Context	Age	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1	tibia		A	15.56	-18.95	0.19	9.4	0.36	3.24	41.05	14.81
5	tibia		A	21.02	-18.89	0.16	9.95	0.47	3.2	43.21	15.75
6	femur		A	17.45	-18.7	0.22	9.93	0.25	3.18	42.67	15.69
7	femur		A	20.26	-18.7	0.1	10.03	0.37	3.17	42.39	15.6
8	femur		A	8.89	-18.67	0.07	12.4	0.25	3.18	43.27	15.89
9	femur		A	17.62	-19	0.14	11.06	0.56	3.12	48.25	18.14
12	femur		A	10.73	-19.1	0.12	10.32	0.05	3.23	42.76	15.45
13	tibia		A	18.68	-18.95	0.06	10.69	0.08	3.18	42.38	15.54
14	femur		A	6.52	-19.14	0.06	10.29	0.33	3.3	34.16	12.09
18	long bone		A	16.3	-18.91	0.04	9.87	0.04	3.2	42.95	15.63
19	femur		A	16.82	-18.01	0.12	10.31	0.02	3.21	42.85	15.58
22	tibia		A	3.85	-19.48	0.04	10.46	0.17	3.36	42.4	14.73
23	tibia		A	18.85	-19.26	0.06	10.38	0.15	3.17	44.16	16.24
25	femur		A	14.23	-19.06	0.15	10.68	0.14	3.2	45.33	16.58
27	femur		A	10.74	-19.21	0.06	10.36	0.23	3.2	41.49	15.11
28	femur		A	10.9	-18.69	0.11	9.44	0.07	3.22	42.26	15.3
29[b]	tibia		A	15.94	-18.8	0.04	11.28	0.26	3.19	43.29	15.85
31	tibia		A	17.78	-18.87	0.04	10.99	0.09	3.19	42.07	15.38
41	tibia		A	14.44	-18.87	0.11	11.04	0.08	3.19	41.59	15.18
43	unk		A	6.28	-18.94	0.07	10.05	0.07	3.26	39.96	14.3
44	unk		A	3.33	-19.45	0.05	9.95	0.11	3.25	37.01	13.3
F25	femur		A	20.33	-17.99	0.04	8.42	0.09	3.17	42.19	15.54

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.8 Villamagna

Table A.8: *Results from Villamagna. Loc. = Location, Ph. = Phase, Or. = Orientation. All bone samples were ribs.EM = Early Medieval, CM=Central Medieval, LM=Late Medieval, OC=Outside Churchyard, Chy=Churchyard, Ch=Church, Mon=Monastery, OM=Outside Monastery, Oth=Other.*

ID	Loc.	Ph.	Age	Sex	Or.	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
2048	OC	LM	A	F	W:E	5.61	-19.74	0.19	6.62	0.55	3.33	20.36	7.12
2064	Chy	LM	A	F	W:E	8.48	-19.59	0.03	6.92	0.35	3.23	42.06	15.18
2066	Chy	LM	A	F	W:E	9.17	-19.67	0.05	7.41	0.1	3.19	39.71	14.53
2080	Chy	LM	A	U	W:E	7.76	-18.44	0.04	10.04	0.1	3.2	40.97	14.94
2084	Chy	LM	A	M	W:E	6	-18.96	0.04	8.59	0.05	3.16	46.84	17.37
2104	Chy	LM	J	U	W:E	3.38	-19.57	0.23	7.74	0.3	3.3	23.79	8.42
2105	Chy	LM	I	U	N/A	3.91	-19.13	0.22	9.82	0.06	3.35	22.65	7.9
2106	Chy	LM	A	M	W:E	5	-19.65	0.2	7.24	0.65	3.4	18.51	6.39
2107	Chy	LM	J	U	W:E	3.78	-19.45	0.23	7	0.12	3.34	20.96	7.37
2108	Chy	LM	A	M	W:E	7.7	-19.5	0.04	6.33	0.24	3.28	30.17	10.74

[a] based on a single mass spectrometer measurement

Continued on next page

[a] based on a duplicate mass spectrometer measurement

Table A.8 – continued from previous page

ID	Loc.	Ph.	Age	Sex	Or.	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
2109[a]	Chy	LM	J	U	W:E	4.63	-19.95	0.15	7.22	0.66	3.25	14.52	5.22
2110	Chy	LM	A	F	W:E	3	-19.5	0.02	7.78	0.16	3.28	39.72	14.15
2111	Chy	LM	A	M	W:E	4.38	-19.28	0.02	7.96	0.05	3.29	42.13	14.94
2150	Chy	LM	A	F	W:E	5.65	-19.76	0.01	7.37	0.06	3.2	40.4	14.75
2153	Chy	LM	J	U	W:E	5.71	-19.74	0.22	7.57	0.34	3.32	17.57	6.17
2159[a]	Chy	LM	J	U	W:E	2.9	-19.58	0.05	7.29	0.12	3.2	22.46	8.21
2163[a]	Chy	LM	I	U	W:E	4.92	-19.01	0.1	9.67	0.2	3.31	25.11	8.89
2170	Chy	LM	A	M	W:E	1.67	-19.91	0.23	5.96	0.52	3.31	14.04	4.96
2173	Chy	LM	J	U	W:E	4	-19.76	0.08	7.1	0.45	3.28	24.94	8.91
2187	Chy	LM	I	U	W:E	4.03	-18.78	0.08	10.69	0.24	3.3	24.14	8.54
2190	Chy	LM	I	U	S:N	4.41	-18.73	0.1	10.37	0.11	3.27	28.36	10.11
2194	Chy	LM	J	U	W:E	5.61	-19.79	0.13	6.74	0.15	3.3	17.47	6.2
2197	Chy	LM	J	U	W:E	4.09	-19.6	0.04	8.13	0.52	3.28	21.84	7.76
2201	Chy	LM	J	U	S:N	3.75	-19.85	0.12	7.46	0.22	3.3	22.74	8.03
2204	Chy	LM	J	U	W:E	3.47	-19.21	0.13	8.98	0.39	3.27	24.26	8.67
2214	Chy	LM	A	F	W:E	4.83	-19.78	0.04	7.38	0.13	3.28	32.76	11.65
2220	Chy	LM	A	M	W:E	4.43	-19.7	0.06	7.96	0.03	3.26	40.7	14.56
2229	Chy	LM	I	U	W:E	5.45	-18.69	0.13	10.02	0.22	3.25	27.53	9.88
2235	Chy	LM	A	M	W:E	3.93	-19.84	0.11	7.4	0.24	3.35	31.08	10.82
2238	Chy	LM	J	U	W:E	4.35	-19.72	0.15	6.92	0.53	3.31	18.38	6.47
2241[a]	Chy	LM	J	U	W:E	2.6	-19.69	0.16	7.65	0.18	3.23	27.54	9.94
2251	Chy	LM	J	U	W:E	4.81	-18.94	0.15	9.05	0.11	3.26	25.77	9.22
2257[a]	Chy	LM	A	U	W:E	4.3	-19.86	0.33	7.55	0.24	3.46	12.98	4.38
2260	Chy	LM	J	U	W:E	4.49	-19.87	0.24	7.89	0.26	3.28	23.54	8.37
2264	Chy	LM	J	U	W:E	4.27	-19.69	0.23	7.9	0.53	3.28	27.52	9.82
2267[a]	Chy	LM	I	U	W:E	3.58	-19.06	0.01	7.72	0.1	3.2	18.8	6.84
2270	Chy	LM	J	U	W:E	4.02	-19.68	0.34	7.62	0.25	3.37	14.21	4.95
2273	Chy	LM	A	M	W:E	8.35	-19.46	0.27	8.11	0.62	3.35	19.78	6.92
2275	Chy	LM	J	U	W:E	4.52	-19.56	0.17	6.7	0.56	3.28	21.8	7.77
2278	Chy	LM	I	U	W:E	4.93	-18.88	0.19	12.58	0.34	3.3	25.77	9.14
2281	Chy	LM	J	U	W:E	4.26	-19.66	0.15	7.88	0.24	3.29	18.59	6.56
2288	Chy	LM	J	U	W:E	3.94	-19.8	0.04	6.05	0.07	3.24	42.47	15.29
2294	Chy	LM	I	U	W:E	3.65	-18.65	0.15	11.04	0.19	3.32	23.5	8.25
2297	Chy	LM	A	M?	W:E	4.26	-19.87	0.03	7.49	0.08	3.27	34.03	12.14
2306	Chy	LM	A	M	W:E	3.3	-19.52	0.25	7.63	0.14	3.32	17.04	5.99
2318	Chy	LM	J	U	W:E	4.03	-19.38	0.33	6.03	0.2	3.35	23.36	8.15
2332	Chy	LM	A	U	W:E	6.15	-19.65	0.11	7.87	0.09	3.2	40.97	14.97
2338	Chy	LM	I	U	W:E	5	-18.58	0.25	9.22	0.61	3.27	33.13	11.82
2348	Chy	LM	J	U	W:E	4.18	-19.69	0.11	6.4	0.59	3.27	34.25	12.24
2354	Chy	LM	I	U	W:E	4	-18.92	0.28	8.67	0.7	3.4	21.73	7.46
2357[a]	Chy	LM	I	U	W:E	3.75	-18.84	0.21	9.65	0.36	3.33	37.43	13.09
2361	Chy	LM	J	U	W:E	4.87	-19.85	0.39	6.07	0.71	3.46	19.56	6.6
2370	Chy	LM	I	U	W:E	5.74	-18.34	0.22	10.09	0.32	3.31	35.16	12.38
2374[a]	Chy	LM	A	F	W:E	5	-20.17	0.25	6.24	0.04	3.31	11.36	4
2377	Chy	LM	I	U	W:E	3.4	-19.2	0.32	8.47	0.31	3.31	31.74	11.22
2380[a]	Chy	LM	A	M	W:E	3.83	-19.76	0.27	7.69	0.27	3.4	15.25	5.26
2388	Chy	LM	A	M	W:E	7.66	-19.01	0.07	9	0.4	3.21	34.67	12.61
2399	Chy	LM	J	U	W:E	4.41	-19.35	0.21	6.29	0.62	3.36	26.03	9.03
2423[a]	Chy	LM	J	U	W:E	4.71	-19.97	0.42	6.49	0.39	3.39	15.43	5.32
2426[a]	Chy	LM	A	F	W:E	2.94	-19.6	0.04	5.93	0.62	3.2	23.07	8.44
2435[a]	Chy	LM	A	U	S:N	4.8	-19.94	0.04	6.01	0.17	3.3	12.95	4.59
2445	OC	LM	I	U	N:S	5.26	-19.16	0.28	9.45	0.26	3.31	35.39	12.5
2454	OC	LM	A	F	N:S	3.86	-19.43	0.17	7.39	0.6	3.3	27.76	9.84

[a] based on a single mass spectrometer measurement

Continued on next page

[a] based on a duplicate mass spectrometer measurement

Table A.8 – continued from previous page

ID	Loc.	Ph.	Age	Sex	Or.	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
2457	OC	LM	I	U	W:E	2.74	-18.89	0.17	9.97	0.74	3.38	23.4	8.07
2460	Ch	LM	J	U	W:E	4.66	-19.67	0.39	5.42	0.6	3.42	16.23	5.53
2469	Ch	LM	A	F	W:E	4.5	-19.62	0.25	7.33	0.61	3.31	22.21	7.83
2474	Ch	LM	I	U	W:E	2.61	-19.45	0.35	7.63	0.61	3.35	27.02	9.42
2477	Ch	LM	A	M	W:E	4.34	-19.59	0.32	8.35	0.46	3.35	18.33	6.37
2490	Ch	LM	I	U	W:E	3.19	-19.17	0.15	10.07	0.08	3.55	21.57	7.1
2547	Oth	Unk	A	U	W:E	5.42	-19.54	0.05	6.94	0.03	3.17	39.39	14.51
2557	Chy	LM	A	F?	W:E	5	-19.6	0.17	7.34	0.28	3.33	21.08	7.38
2567	Chy	LM	J	U	W:E	3.67	-19.48	0.21	7.05	0.5	3.48	23.13	7.79
2584	Chy	LM	A	F	W:E	3.61	-19.53	0.06	7.79	0.14	3.25	37.23	13.35
2587	Chy	LM	J	U	W:E	4.07	-19.35	0.17	8.55	0.34	3.47	24.79	8.35
2590	Chy	LM	A	M	W:E	5.34	-19.56	0.06	7.58	0.16	3.33	31.37	11.01
2596	Chy	LM	I	U	S:N	3.28	-18.94	0.27	10.65	0.48	3.43	17.27	5.86
2599	Chy	LM	J	U	W:E	3.88	-19.81	0.29	6.75	0.45	3.45	14.39	4.86
2606	Chy	LM	A	M	W:E	2.93	-19.44	0.07	7.97	0.24	3.44	22.07	7.47
2612^a	Chy	LM	A	M	W:E	3.64	-19.67	0.04	7.35	0.31	3.23	13.91	5.02
2615	OC	LM	A	F	W:E	8.46	-19.02	0.07	7.68	0.46	3.24	31.14	11.22
2621	Chy	LM	A	F	W:E	5.32	-19.57	0.11	7.38	0.34	3.2	38.19	13.9
2625	Chy	LM	I	U	S:N	3.64	-18.06	0.14	11.92	0.35	3.47	26.54	8.93
2631	Chy	LM	I	U	W:E	2.42	-19.22	0.1	9.2	0.07	3.33	42.27	14.83
2634^a	Chy	LM	I	U	W:E	2.86	-19.96	0.16	6.88	0.68	3.46	13.89	4.68
2641^a	Chy	LM	I	U	W:E	2.5	-19.28	0.13	8.01	0.49	3.47	21.78	7.35
2666	Chy	LM	A	M	W:E	12.79	-19.32	0.14	8.14	0.49	3.23	28.71	10.37
2669	Chy	LM	A	U	W:E	3.24	-19.1	0.11	7.46	0.25	3.55	16.83	5.54
2673	Chy	LM	A	U	W:E	4.72	-19.27	0.09	7.13	0.09	3.2	41.29	15.06
2685	Chy	LM	A	M	W:E	9.71	-19.12	0.13	7.27	0.42	3.22	32.48	11.77
2688	Chy	LM	A	M	W:E	4.44	-19.34	0.03	8.68	0.25	3.22	39.36	14.26
2691	Chy	LM	I	U	W:E	5.22	-19.11	0.05	9.51	0.1	3.27	41.32	14.74
2694^a	Chy	LM	I	U	W:E	2.59	-18.18	0.28	11.09	0.66	3.54	21.54	7.1
2703^a	Chy	LM	J	U	W:E	2.94	-19.96	0.36	6.43	0.61	3.44	12.21	4.15
2723	Chy	LM	A	U	W:E	3.58	-19.47	0.08	7.04	0.05	3.25	39.95	14.35
2726	Chy	LM	A	M	N:S	4.73	-19.24	0.07	8.8	0.18	3.27	25.9	9.24
2757^a	Chy	LM	A	M	W:E	4.11	-19.22	0.04	7.99	0.46	3.4	11.74	4.04
2763	Chy	LM	F	U	W:E	3.45	-19.2	0.35	7.25	0.31	3.38	19.02	6.53
2769	Chy	LM	A	F	N:S	4	-19.6	0.14	7.81	0.04	3.32	25.41	8.94
2772^a	Chy	LM	A	F	W:E	3.29	-19.76	0.07	6.24	0.16	3.23	32.38	11.71
2780^a	Chy	LM	I	U	W:E	2.07	-18.97	0.33	9.64	0.6	3.57	17.11	5.59
2801	Chy	LM	A	F	W:E	3.02	-19.96	0.12	6.67	0.39	3.31	18.93	6.67
2809	Chy	LM	A	U	S:N	3.48	-18.94	0.12	12.93	0.29	3.23	40.82	14.76
2812^a	Chy	LM	A	F?	W:E	3.6	-19.71	0.04	8.24	0.64	3.22	13.62	4.93
2848	Chy	LM	I	U	W:E	7.69	-19.07	0.02	9.47	0.04	3.18	42.87	15.73
2851	Chy	LM	J	U	W:E	5	-19.1	0.03	7.87	0.01	3.23	39.45	14.24
2854	Chy	LM	A	U	W:E	5.75	-19.88	0.01	7.27	0.07	3.2	42.3	15.42
2869^a	Chy	LM	A	M	W:E	5	-19.53	0.04	7.53	0.01	3.27	36.84	13.16
2872	Chy	LM	A	M	W:E	4.62	-19.42	0.12	7.57	0.46	3.24	38.21	13.79
2875	Chy	LM	A	M?	W:E	4.86	-19.89	0.06	6.87	0.13	3.23	40.4	14.61
2878	Chy	LM	J	U	W:E	3.77	-19.45	0.04	7.92	0.06	3.25	43.96	15.84
2887	Chy	LM	A	F	W:E	4.46	-19.74	0.05	7.05	0.42	3.24	35.74	12.84
2890	Chy	LM	A	M	W:E	6.06	-19.44	0.18	8.04	0.73	3.28	32.23	11.54
2893^a	Chy	LM	A	M	W:E	3.18	-19.4	0.25	7	0.28	3.39	21.78	7.5
2899	Chy	LM	A	U	W:E	4.85	-19.31	0.2	7.57	0.37	3.29	25.96	9.21
2910	Chy	LM	J	U	W:E	4.24	-19.85	0.12	6.86	0.37	3.23	40.29	14.55
2916	Chy	LM	A	F?	W:E	2.38	-19.44	0.11	8.9	0.27	3.27	39.76	14.21

[a] based on a single mass spectrometer measurement

Continued on next page

[a] based on a duplicate mass spectrometer measurement

Table A.8 – continued from previous page

ID	Loc.	Ph.	Age	Sex	Or.	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
2919	Chy	LM	A	F	W:E	4.84	-19.77	0.35	7.52	0.6	3.36	17.28	6.01
2925	Chy	LM	J	U	W:E	2.94	-19.66	0.13	8.31	0.29	3.23	41.59	15.06
2928	Chy	LM	A	M	W:E	5.14	-19.49	0.03	7.68	0.08	3.26	39.64	14.21
2932	Chy	LM	A	U	W:E	2.31	-19.38	0.06	6.88	0.7	3.29	34.37	12.19
2935	Chy	LM	I	U	W:E	4.22	-18.56	0.08	10.16	0.12	3.18	42.18	15.46
2938	Chy	LM	J	U	W:E	5.44	-19.55	0.02	6.88	0.01	3.21	41.55	15.12
2942	Chy	LM	A	U	W:E	4.38	-19.43	0.07	8.06	0.13	3.19	40.78	14.9
2948	Chy	LM	I	U	W:E	8.31	-18.75	0.04	10.66	0.07	3.19	39.82	14.55
2954	Chy	LM	J	U	W:E	2.58	-18.96	0.12	9.79	0.26	3.23	41.24	14.89
2960	Chy	LM	I	U	W:E	3.91	-19.67	0.05	7.71	0.06	3.3	36	12.7
2969	Chy	LM	A	U	W:E	6.57	-19.78	0.04	5.34	0.07	3.18	40.56	14.89
2975[a]	Chy	LM	J	U	W:E	3.47	-20.04	0.01	6.81	0.07	3.3	14.36	5.09
2978[a]	Chy	LM	A	F	S:N	5.48	-20.04	0.18	7.46	0.16	3.3	11.62	4.11
2981	Chy	LM	A	M	W:E	2.84	-19.85	0.15	6.48	0.24	3.34	17.03	5.91
2997	Chy	LM	A	M	W:E	3.65	-19.64	0.31	8.59	0.57	3.37	15.2	5.24
3022	Ch	LM	A	M	S:N	5.48	-18.64	0.21	8.15	0.06	3.26	24.54	8.79
3042	Ch	LM	A	M	S:N	5	-18.98	0.28	7.35	0.25	3.3	19.72	6.97
3053	Ch	LM	I	U	W:E	3.69	-19.22	0.04	8.8	0.47	3.33	36.09	12.65
3059[a]	Ch	LM	I	U	W:E	2.88	-18.89	0.23	8.67	0.47	3.49	23.84	7.98
3060	Ch	LM	I	U	W:E	4.14	-19.32	0.22	7.75	0.52	3.2	42.68	15.59
3061	Ch	LM	A	M	W:E	6.3	-19.59	0.1	7.28	0.46	3.26	28.76	10.3
3069	Ch	LM	A	M	W:E	5.41	-19.46	0.15	8.4	0.08	3.27	25.8	9.22
3074[a]	Ch	LM	J	U	W:E	2.69	-19.72	0.16	6.35	0.2	3.45	19.7	6.7
3085	Ch	LM	I	U	W:E	3.45	-19.16	0.08	10.76	0.43	3.23	42.07	15.22
3091	Ch	LM	J	U	W:E	5.61	-19.36	0.18	8.53	0.63	3.17	44.12	16.29
3094	Ch	LM	I	U	W:E	5.69	-18.86	0.06	8.8	0.69	3.26	39.28	14.06
3097	Ch	CM	A	M	W:E	8.31	-19.21	0.09	8.56	0.16	3.21	44.39	16.17
3102[a]	Ch	CM	A	M	W:E	2.75	-19.28	0.05	6.71	0.31	3.23	15.21	5.5
3500	Chy	LM	A	U	W:E	8.17	-19.38	0.11	7.45	0.1	3.23	41.1	14.88
3506[a]	Chy	LM	A	M	W:E	4.23	-19.37	0.03	7.92	0.06	3.18	20.14	7.39
3515	Chy	LM	J	U	N:S	5.06	-19.44	0.07	6.59	0.08	3.23	39.22	14.15
3540	Chy	LM	J	U	W:E	5.24	-19.81	0.02	7.11	0.05	3.3	43.1	15.22
3547	Oth	Unk	A	M	W:E	6.1	-19.45	0.16	7.42	0.59	3.28	26.13	9.3
3553	Chy	LM	A	U	W:E	9.52	-19.21	0.08	7.84	0.11	3.23	41.86	15.11
3562	Chy	LM	A	U	W:E	3.52	-19.59	0.08	8.36	0.35	3.35	35.8	12.48
3581	Chy	LM	A	F	W:E	2.14	-19.78	0.03	7.57	0.13	3.28	40.82	14.5
3592[a]	Chy	LM	A	M	W:E	4.15	-19.33	0.21	7.76	0.47	3.33	21.67	7.58
3616[a]	Chy	LM	A	F	W:E	1.67	-19.54	0.11	7.18	0.4	3.29	24.04	8.52
3622	Chy	LM	A	F	W:E	3.48	-19.68	0.01	7.57	0.06	3.29	35.76	12.69
3634	Chy	LM	J	U	W:E	2.98	-20.01	0.03	7.18	0.32	3.25	41.03	14.7
3671	Chy	LM	A	M	W:E	6.98	-18.95	0.1	9.45	0.65	3.26	40.69	14.57
3674	Chy	LM	A	M	W:E	8.22	-19.11	0.27	9.54	0.34	3.28	29.03	10.35
3677	Chy	LM	A	M	W:E	2.04	-19.54	0.17	7.02	0.25	3.32	29.43	10.35
3701	Chy	LM	I	U	S:N	2.86	-19.93	0.15	8.63	0.57	3.34	37.38	13.05
3707	Chy	LM	A	F	S:N	4.18	-19.98	0.3	7.01	0.66	3.38	16.53	5.7
3710	Chy	LM	A	U	W:E	3.33	-19.39	0.04	8.11	0.26	3.31	37.6	13.27
3713	Chy	LM	J	U	W:E	5.12	-19.45	0.06	7.52	0.13	3.29	34.6	12.28
3716	Chy	LM	I	U	S:N	3.58	-19.46	0.1	9.14	0.13	3.26	37.53	13.46
3724	Chy	LM	J	U	W:E	6.56	-19.54	0.06	6.67	0.14	3.27	39.8	14.23
3734	Chy	LM	A	F	W:E	5.82	-19.26	0.12	8.8	0.26	3.21	38.53	14.06
3737	Oth	Unk	A	M	W:E	4.1	-19.54	0.08	8.05	0.12	3.21	38.64	14.03
3740	Chy	LM	I	U	N:S	6.46	-18.89	0.13	8.33	0.39	3.26	37.96	13.6
3762	Chy	LM	I	U	N:S	5	-19.21	0.06	9	0.22	3.23	39.93	14.46

[a] based on a single mass spectrometer measurement

Continued on next page

[a] based on a duplicate mass spectrometer measurement

Table A.8 – continued from previous page

ID	Loc.	Ph.	Age	Sex	Or.	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
3765	Chy	LM	J	U	N:S	6.53	-18.9	0.04	9.24	0.05	3.21	40.65	14.77
3781	Chy	LM	A	U	N:S	3.16	-19.25	0.1	7.62	0.27	3.3	40.18	14.19
3830	Chy	LM	A	F	W:E	5.54	-19.53	0.06	7.69	0.09	3.21	38.68	14.06
3833	Chy	EM	I	U	W:E	4.58	-19.21	0.06	9.97	0.19	3.26	39.39	14.09
3850	Chy	LM	A	M	W:E	7.23	-19.5	0.08	7.57	0.09	3.24	41.77	15.08
3854	Chy	LM	A	U	W:E	5.56	-19.15	0.03	8.75	0.12	3.32	37.22	13.09
3885	Chy	EM	A	F	W:E	1.47	-19.77	0.06	7.13	0.19	3.33	40.18	14.09
3898	Oth	EM	A	M	W:E	0	-19.43	0.09	7.59	0.12	3.23	41.84	15.11
3911	Chy	EM	A	M	W:E	2.86	-19.2	0.09	7.41	0.45	3.23	42.48	15.35
3914	Chy	EM	J	U	W:E	1.8	-19.96	0.05	6.51	0.05	3.29	43.12	15.27
4062	OC	LM	A	M	N:S	3.98	-19.43	0.37	7.16	0.62	3.37	15.06	5.19
4067	OC	LM	A	U	N:S	6.1	-17.73	0.15	10.05	0.06	3.45	26.07	8.83
4077	OC	LM	A	M?	N:S	3.78	-19.18	0.27	6.56	0.72	3.33	19.51	6.84
4084	Mon	LM	A	M	N:S	5.96	-19.28	0.02	10.54	0.01	3.28	39.77	14.15
4087	Chy	CM	A	U	W:E	6.42	-19.46	0.06	6.37	0.13	3.19	43.04	15.71
4097	OM	CM	A	U	S:N	1.53	-19.18	0.27	8.93	0.18	3.2	42.22	15.4
4101[a]	OM	CM	J	U	S:N	2.08	-19.89	0.25	5.16	0.38	3.52	18.88	6.28
4118	OM	CM	A	F?	N:S	3.45	-18.42	0.07	9.3	0.3	3.24	36.34	13.09
4146	OM	CM	A	M?	S:N	3.58	-19.35	0.38	8.56	0.21	3.35	16.48	5.76
4172[a]	OM	CM	A	U	N:S	1.84	-18.75	0.04	8.73	0.15	3.26	43.57	15.61
4181	OM	CM	A	M?	N:S	9.18	-18.91	0.01	9.49	0.26	3.18	39.67	14.52
4193[a]	OM	CM	J	U	N:S	2.5	-18.7	0.07	7.06	0.22	3.19	44.45	16.29
4272	Chy	CM	A	M	W:E	5	-19.55	0.12	6.24	0.12	3.25	40.99	14.72
4274	Chy	CM	A	M	W:E	6.87	-18.09	0.05	9.85	0.06	3.21	41.38	15.05
4282	Chy	CM	J	U	W:E	7.82	-18.94	0.06	6.26	0.13	3.23	41.01	14.79
4285	Chy	CM	A	F	W:E	6.88	-19.58	0.02	6.85	0.07	3.2	41.4	15.1
4342	Mon	CM	A	M	W:E	7.29	-18.72	0.04	8.64	0.08	3.29	39.61	14.08
4348	Mon	CM	A	M	N:S	5.26	-19.47	0.04	11.02	0.08	3.27	39.52	14.12
4370	Mon	CM	A	M	W:E	7.04	-19.42	0.02	7.35	0.09	3.23	41.98	15.17
4375	Chy	CM	A	M	W:E	5.74	-18.55	0.05	6.03	0.04	3.21	42.68	15.52
4378	Chy	EM	J	U	W:E	6.27	-19.76	0.03	5.91	0.04	3.2	41.33	15.06
4390	Mon	CM	A	M	W:E	11.45	-19.31	0.48	7.77	0.08	3.23	42.45	15.32

[a] based on a duplicate mass spectrometer measurement

A.9 Villamagna Fauna

Table A.9: *Faunal results from Villamagna*

ID	Bone	Context	Species	% yield	δ^{13}C	1σ	δ^{15}N	1σ	C/N	%C	%N
1	acetabulum	LM	sheepgoat	14.06	-20.16	0.08	4.41	0.29	3.2	37.91	13.84
2	long bone	Roman	sheepgoat	12.46	-20.98	0.06	6.21	0.24	3.2	41.2	15.02
3	maxilla	Roman	sheepgoat	18.1	-19.23	0.07	4.95	0.46	3.21	39.79	14.44
4	long bone	LM	sheepgoat	12.76	-20.78	0.06	4.03	0.27	3.24	41.77	15.07
5	long bone	LM	pig	8.9	-20.18	0.08	5.03	0.2	3.17	37.47	13.78
8	long bone	LM	sheepgoat	15.9	-21.64	0.02	4.12	0.64	3.26	35.9	12.86
9	mandible	LM	sheepgoat	8.47	-20.73	0.09	6.72	0.59	3.18	34.83	12.79
11	scapula	LM	pig	10.8	-20	0.01	4.12	0.48	3.26	32.87	11.75
12	long bone	LM	pig	3.73	-20.84	0.19	3.26	0.79	3.38	23.99	8.29
13	mandible	LM	pig	2.72	-20.62	0.19	4.51	0.51	3.45	22.92	7.75
14	humerus	LM	sheepgoat	12.65	-20.56	0.06	3.84	0.51	3.21	40.04	14.55
15	mandible	LM	cattle	6.28	-18.41	0.08	5.92	0.77	3.3	27.56	9.74
16	long bone	LM	pig	7.44	-21	0.04	4.08	0.14	3.21	37.93	13.79
17	mandible	LM	pig	2.88	-20.17	0.12	2.5	0.75	3.38	22.28	7.7
18	scapula	LM	pig	3.42	-20.74	0.26	4.61	0.52	3.49	14.62	4.88
19	long bone	LM	cattle	8.24	-19.98	0.15	4.84	0.64	3.28	31.29	11.16
20	long bone	LM	cattle	5.56	-20.21	0.04	3.95	0.27	3.23	41.34	14.93
22	long bone	LM	sheepgoat	3.59	-20.97	0.05	5.11	0.51	3.29	41.13	14.55
23	long bone	LM	sheepgoat	8.98	-21.53	0.09	3.68	0.72	3.28	31.27	11.14
24	long bone	LM	pig	4.59	-21.05	0.32	3.03	0.82	3.49	13.48	4.5
25	long bone	LM	sheepgoat	17.47	-21.01	0.05	3.14	0.21	3.18	40.19	14.75
27	tarsus?	LM	cattle	5.65	-21.25	0.02	4.52	0.12	3.26	40.45	14.5
28	tarsus?	LM	cattle	9.87	-20.45	0.04	4.11	0.24	3.25	40.9	14.7
29	mandible	Roman	pig	14.23	-20.53	0.08	5.25	0.22	3.18	43.2	15.85
30	long bone	Roman	pig	17.78	-20.63	0.22	4.09	0.06	3.19	46.25	16.92
32	tarsus?	LM	cattle	8.73	-20.49	0.01	3.77	0.21	3.28	43.37	15.41
33	mandible	LM	cattle	1.88	-20.28	0.02	5.75	0.11	3.26	39.22	14.03
36	fibula	LM	horse	14.58	-20.56	0.06	3.96	0.28	3.22	41.01	14.88
37	fibula	LM	horse	8.22	-20.56	0.04	4.13	0.21	3.23	42.7	15.42

[a] based on a single mass spectrometer measurement

[b] based on a duplicate mass spectrometer measurement

A.10 Meta-analysis: Mediterranean Fauna

Table A.10: *Summary of previously published domesticated herbivore collections from the Mediterranean included in the Meta-analysis. Referenced studies are as follows: * This study, 1 - Bourbou and Richards, 2007, 2 - Craig et al., 2009, 3 - Fuller et al., 2010, 4 - Garvie-Lok, 2001, 5 - Keenleyside et al., 2009, 6 - Mundee, 2010, 7 - Prowse et al., 2004.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Kastella	LM	C	9	-20.33	0.72	5.12	1.03	1
Velia	R	C	8	-21.01	0.99	4.44	1.94	2
Ibiza	EM	C	12	-20.08	0.74	5.89	1.38	3
Ibiza	LM	C	19	-19.87	0.66	6.76	2.06	3
Athens	LM	C	20	-19.94	0.64	6.08	2.21	4
Corinth	LM	C	6	-19.77	0.42	3.97	0.77	4
Mitilini	LM	C	7	-21.26	0.43	5.9	1.46	4
Leptiminus	R	C	6	-19.35	0.99	9.23	2.67	5
Barbastro	LM	I	4	-18.2	0.29	7.98	0.43	6
Albarracin	LM	I	11	-19.94	0.46	6.17	2.15	6
Almacabra	LM	I	9	-19.94	0.34	6.66	2.2	6
Benipeixcar	LM	C	15	-18.72	1.7	5.17	1.75	6
Huesca	LM	I	12	-19.41	0.5	7.32	2.4	6
Valencia	LM	C	27	-19.25	1.2	6.65	2.17	6
Zaragoza	LM	I	16	-18.96	1.08	7.52	2.2	6
VMA	LM	I	23	-20.57	0.66	4.31	0.97	*
VMA	R	I	4	-20.34	0.77	5.12	0.88	*
IsolaSacra	R	C	9	-20.56	0.64	5.2	1.4	7

All values ‰

A.11 Meta-analysis: Central European Fauna

Table A.11: *Summary of previously published domesticated herbivore collections from Central Europe included in the Meta-analysis. Referenced studies are as follows: 1 - Hakenbeck et al., 2010, 2 - McGlynn, 2007, 3 - Herrscher et al., 2001, 4 - Schutkowski et al., 1999.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Bavaria	EM	I	37	-21.21	0.61	6.59	1.55	1
Volders	EM	I	17	-21.84	0.43	5.64	1.29	2
Grenoble	LM	I	9	-20.96	0.5	4.74	1.04	3
Klettham	R	I	12	-21.49	0.51	8.07	0.92	1
Weingarten	EM	I	1	-21.9	-	5.4	-	4

All values ‰

A.12 Meta-analysis: Northern European Fauna

Table A.12: *Summary of previously published domesticated herbivore collections from Northern Europe included in the Meta-analysis. Referenced studies are as follows: 1 - Ervynck et al., 1999, 2 - Jørkov et al., 2010, 3 - Polet and Katzenberg, 2003, 4 - Reitsema et al., 2010, 5 - Schäuble, 2005, 6 - Yoder, 2010.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Ename	LM	I	5	-22.04	0.34	6.780000	1.2070626	1
Bofa Tornegard	R	I	5	-21.68	0.33	7.040000	1.3088163	2
Hagerup	R	I	1	-21.6	-	6.700000	-	2
Himlingoje	R	C	3	-22.03	0.23	7.533333	2.1548395	2
Kassebjerggard	R	I	3	-21.77	0.25	6.566667	0.6350853	2
Skovgarde	R	C	2	-22.25	0.35	7.850000	1.2020815	2
Koksijde	LM	C	4	-21.3	0.67	5.350000	1.0344080	3
Giecz	LM	I	3	-21.33	0.74	6.366667	0.5131601	4
Bernau	LM	I	6	-21.4	0.78	7.016667	0.4262237	5
Tasdorf	LM	I	4	-21.33	0.91	7.125000	0.9178780	5
Usedom	LM	C	3	-21.17	0.42	7.466667	1.8770544	5
Om Kloster	LM	I	3	-21.54	0.27	6.710000	0.9224424	6

All values ‰

A.13 Meta-analysis: England Fauna

Table A.13: *Summary of previously published domesticated herbivore collections from Northern Europe included in the Meta-analysis. Referenced studies are as follows: 1 - Chenery et al., 2010, 2 - Chenery et al., 2011, 3 - Lightfoot et al., 2009, 4 - Müldner and Richards, 2005, 5 - Müldner and Richards, 2007a, 6 - Müldner et al., 2009, 7 - Privat et al., 2002.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Gloucester	R	I	6	-21.57	0.29	6.23	0.67	1
Catterick	R	I	21	-21.52	0.33	6.26	1.62	2
Yarnton	R	I	27	-21.53	0.38	7.62	1.94	3
St. Giles	LM	I	21	-21.66	0.62	5.86	1.35	4
Wharram Percy	LM	I	16	-21.63	0.42	5.85	1.4	4
York	EM	I	13	-21.73	0.42	6.22	1.43	5
York	LM	I	37	-21.61	0.44	6.61	1.81	5
York	R	I	24	-21.88	0.51	6.71	1.31	5
Whithorn	LM	C	15	-21.79	0.63	8.33	2.03	6
Berinsfield	EM	I	7	-21.4	0.3	5.89	0.38	7

All values ‰

A.14 Meta-analysis: Mediterranean Humans

Table A.14: *Summary of previously published human collections from the Mediterranean included in the Meta-analysis. Referenced studies are as follows: 1 - Garvie-Lok, 2001, 2 - Mundee, 2010, 3 - Prowse et al., 2004, 4 - Salamon et al., 2008, 5 - Fornaciari, 2008, 6 - Fuller et al., 2010, 7 - Keenleyside et al., 2009, 8 - Rutgers et al., 2009, 9 - Craig et al., 2009, 10 - Crowe et al., 2010.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Agora Ayios Nicolaos	LM	C	9	-19.44	0.23	9.57	0.86	1
Agora Hephaisteion	LM	C	10	-19.35	0.34	11.05	1.21	1
Albarracin Almacabra	LM	I	31	-18.99	0.19	10.79	0.65	2
ANAS	R	I	14	-19.41	0.37	9.5	1.79	3, 10
Athens	LM	I	1	-18.6	NA	8.3	NA	1
Benipeixcar	LM	C	20	-16.36	0.95	10.68	0.58	2
Castro dei Volsci	EM	I	14	-19.83	0.28	7.48	0.61	4
Colegiata	LM	C	24	-17.24	1.01	10.25	0.78	2
Corinth Frankish	LM	C	10	-18.75	0.34	10.14	0.93	1

All values ‰

Continued on next page

Table A.14 – continued from previous page

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Corinth Ottoman	LM	C	9	-17.98	1.12	10.14	2.01	1
Corinth Ruined Church	LM	C	8	-18.93	0.21	9.65	0.27	1
Florence	LM	I	12	-18.15	0.39	12.09	0.72	5
Ibiza	LM	C	21	-18.09	1.31	10.88	1.02	6
Ibiza	EM	C	35	-19.02	0.38	11.03	0.9	6
Isola Sacra	R	C	189	-18.74	0.35	11.02	1.05	3
Jaca Plaza Biscos	LM	I	25	-18.42	1.15	9.99	0.82	2
Kastella	LM	C	15	-18.86	0.33	9.11	0.86	1
Leptiminus	R	C	54	-17.78	0.59	12.94	1.27	7
Mitilini Gatteliusi	LM	C	8	-19.31	0.28	8.34	0.88	1
Naples	LM	C	22	-18.01	0.6	11.27	0.9	5
Nemea Early Christian	EM	I	16	-18.97	0.84	8.69	0.61	1
Nemea Medieval	LM	I	18	-19.06	0.27	8.72	0.51	1
Petras	LM	C	12	-19.15	0.33	9.46	0.7	1
Rome Cancelleria	LM	I	33	-19.04	0.28	11.07	1.7	4
Servia	LM	I	14	-18.74	0.35	8.7	0.61	1
St. Callixtus	R	I	16	-19.69	0.42	10.63	0.54	8
Valencia Amoina	LM	C	7	-17.31	1.06	12.93	2.06	2
Valencia Calle Alta	LM	C	21	-18.41	0.96	10.75	0.74	2
Valencia Calle Pintor	LM	C	3	-16.03	0.74	12.03	0.25	2
Valencia Calle Sagunto	LM	C	7	-16.6	1.25	12.4	1.17	2
Valencia San Andres	LM	C	4	-18.2	0.14	11.18	0.5	2
Valencia San Vicente	LM	C	15	-18.45	0.65	10.8	2.1	2
Velia	R	C	117	-19.44	0.25	8.65	1.33	9
Zaragoza Babal-Qibla	LM	I	23	-18.92	0.34	10.49	1.16	2
Zaragoza LaSeo	LM	I	2	-18.85	0.35	10	2.83	2
Zaragoza Predicadores	EM	I	13	-19.12	0.29	11.53	1.54	2
Zaragoza RomanTheatre	EM	I	3	-18.2	0.44	10.73	1.19	2

All values ‰

A.15 Meta-analysis: Central Europe Humans

Table A.15: *Summary of previously published human collections from Central Europe included in the Meta-analysis. Referenced studies are as follows: 1 - Hakenbeck et al., 2010, 2 - Herrscher et al., 2001, 3 - McGlynn, 2007, 4 - Schutkowski et al., 1999.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Altenerding	EM	I	67	-19.43	0.49	9.64	0.72	1
Grenoble	LM	I	34	-19.95	0.38	8.68	0.92	2
Klettham	R	I	10	-19.32	0.81	9.45	0.58	1
Straubing-Bajuwarenstrasse	EM	I	95	-19.69	0.36	9.56	0.69	1
Volders	EM	I	103	-20.01	0.56	10.02	0.95	3
Weingarten	EM	I	37	-19.77	0.66	8.69	0.65	4

All values ‰

A.16 Meta-analysis: Northern Europe Humans

Table A.16: *Summary of previously published domesticated herbivore collections from Northern Europe included in the Meta-analysis. Referenced studies are as follows: 1 - Jørkov et al., 2010, 2 - Ervynck et al., 1999, 3 - Schäuble, 2005, 4 - Reitsema et al., 2010, 5 - Polet and Katzenberg, 2003.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
Anaes	R	C	5	-20.54	0.18	10.98	0.31	1
Antwerp	LM	I	2	-19.4	0	11.15	0.35	2
Bernau	LM	I	19	-19.79	0.33	12.24	0.56	3
Bogebjerggard	R	C	12	-20.38	0.29	10.93	0.65	1
Giecz	LM	I	24	-18.89	0.36	9.19	0.59	4
Hagerup	R	I	1	-21.1	-	10.5	-	1
Himlingoje	R	C	4	-20.58	0.22	11.3	0.18	1
Hoby	R	C	1	-20.1	-	11.9	-	1
Juellinge	R	I	2	-20.65	0.21	11.9	0.42	1
Koksijde	LM	C	13	-19	0.47	11.14	0.94	5
Leuven	LM	I	3	-19.53	1.24	10.63	0.31	2
Namur	EM	I	5	-20.2	0.27	8.9	0.68	2
Simonsborg	R	I	19	-20.56	0.21	10.75	0.45	1
Skovgarde	R	C	10	-20.52	0.13	10.6	0.32	1
Slusegard	R	I	8	-20.55	0.78	11.59	0.82	1
Tasdorf	LM	I	20	-19.93	0.32	10.02	1.16	3
Tongeren	EM	I	2	-19.8	0.14	11.65	0.07	2
Usedom	LM	C	20	-19.43	0.42	10.6	0.92	3
Varpeley	R	C	8	-20.45	0.18	10.86	0.61	1

All values ‰

A.17 Meta-analysis: England Humans

Table A.17: *Summary of previously published human collections from England. Referenced studies are as follows: 1 - Müldner et al., 2011, 2 - Hull, 2008, 3 - Privat et al., 2002, 4 - Chenery et al., 2011, 5 - Müldner and Richards, 2007b, 6 - Chenery et al., 2010, 7 - Bayliss et al., 2004, 8 - Richards et al., 1998, 9 - Fuller et al., 2006b, 10 - Müldner and Richards, 2005, 11 - Richards et al., 2002, 12 - Müldner et al., 2009, 13 - Müldner and Richards, 2007a.*

Site	Date	CI	N	δ^{13}C	1σ	δ^{15}N	1σ	Study
3DT	R	I	49	-19.48	0.66	10.88	0.77	1
6DT	R	I	29	-19.61	1.16	11.2	1.01	1
Alton	EM	I	31	-20.49	0.28	9.01	0.68	2
Bergh Apton	EM	I	12	-20.87	0.48	9.65	0.53	2
Berinsfield	EM	I	72	-20.12	0.2	9.74	0.68	3
Burgh Castle	EM	C	28	-19.78	0.63	10.9	1.18	2
Caister-by-Yarmouth	EM	C	18	-19.51	0.84	12.27	1.52	2
Catterick	R	I	36	-20.07	0.48	10.78	0.7	4
Droxford	EM	I	34	-20.18	0.38	8.89	0.74	2
Fishergate	LM	I	155	-19.09	0.64	12.78	1.3	5
Gloucester	R	I	26	-19.74	0.51	11.19	0.93	6
Morningthorpe	EM	I	19	-20.68	0.35	10.42	0.63	2
Norwich	LM	I	12	-19.47	1.2	11.35	0.86	7
Norwich	EM	I	5	-18.94	0.48	10.5	0.64	7
Oxborough	EM	I	3	-20.32	0.55	9.53	0.62	2
Portway	EM	I	48	-19.85	0.59	8.22	0.84	2
Poundbury	R	C	49	-19.25	0.77	9.2	1.2	8
Queenford Farm	EM	I	36	-19.69	0.41	10.28	1.01	9
Shavard	EM	I	12	-19.66	0.2	8.76	0.47	2
South Acre	EM	I	12	-19.14	0.35	11.67	0.76	2
Spong Hill	EM	I	6	-20.8	0.45	10.54	0.45	2
St Giles	LM	I	16	-19.07	0.51	12.56	0.79	10
Swaffham	EM	I	10	-20.33	0.53	9.66	1.02	2
Towton	LM	I	11	-19.39	0.52	12.69	0.71	10
Warrington	LM	C	18	-19.83	0.55	11.95	1	10
Westgarth	EM	I	54	-20.13	0.3	9.91	0.61	2
Wharram Percy	LM	I	28	-19.67	0.35	9.18	1.11	11
WhithornL	LM	C	7	-20.43	0.71	11.29	0.52	12
WhithornP	LM	C	6	-19.35	0.36	12.63	0.81	12
Winnall	EM	I	33	-20.21	0.26	9.1	0.85	2
Worthy Park	EM	I	33	-20.34	0.33	8.65	1.32	2
York	LM	I	62	-19.55	0.66	11.64	1.27	13
York	R	I	60	-19.54	0.58	11.22	0.76	13
York	EM	I	33	-20.04	0.31	10.25	0.91	13

All values ‰

B

Statistical Analysis

B.1 Italian pairwise site comparisons

Table B.1: *Table showing the significance of pairwise comparisons of $\delta^{13}C$ differences between sites. Significance codes ($p < 0.001$ =***, $p < 0.01$ = **, $p < 0.05$ =*) based on Tukey's Honestly Significant Difference family-wise comparison for the 95% confidence interval.*

Site-Site	ANAS	Castro dei Volsci	Catacombs	CD	CNM	Esanatoglia	Florence	Isola Sacra	MP	Naples	ODF	Pompeii	Palestrina	Rome	Velia
Castro dei Volsci	-0.42	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Catacombs	-0.28	0.14	–	–	–	–	–	–	–	–	–	–	–	–	–
Casale del Dolce	-0.6 ***	-0.18	-0.32	–	–	–	–	–	–	–	–	–	–	–	–
CNM	-0.19	0.23	0.09	0.41 **	–	–	–	–	–	–	–	–	–	–	–
Esanatoglia	-0.07	0.35	0.21	0.53 *	0.12	–	–	–	–	–	–	–	–	–	–
Florence	1.25 ***	1.67 ***	1.53 ***	1.85 ***	1.44 ***	1.32 ***	–	–	–	–	–	–	–	–	–
Isola Sacra	0.67 ***	1.09 ***	0.95 ***	1.27 ***	0.86 ***	0.74 ***	-0.58 ***	–	–	–	–	–	–	–	–
MP	0.34	0.76 ***	0.62 **	0.94 ***	0.53 **	0.41	-0.91 ***	-0.33	–	–	–	–	–	–	–
Naples	1.4 ***	1.82 ***	1.68 ***	2 ***	1.59 ***	1.47 ***	0.15	0.73 ***	1.06 ***	–	–	–	–	–	–
ODF	-0.31	0.11	-0.03	0.29	-0.12	-0.24	-1.57 ***	-0.98 ***	-0.65 ***	-1.71 ***	–	–	–	–	–
Pompeii	0.51 **	0.94 ***	0.79 ***	1.12 ***	0.7 ***	0.59 *	-0.74 ***	-0.16	0.17	-0.89 ***	0.83 ***	–	–	–	–
Palestrina	-0.04	0.38	0.24	0.56	0.15	0.03	-1.29 ***	-0.71 **	-0.38	-1.44 ***	0.27	-0.56	–	–	–
Rome	0.37	0.79 ***	0.65 ***	0.97 ***	0.56 ***	0.44	-0.89 ***	-0.3 **	0.03	-1.03 ***	0.68 ***	-0.15	0.41	–	–
Velia	-0.03	0.39 *	0.25	0.57 ***	0.16	0.04	-1.29 ***	-0.7 ***	-0.37	-1.43 ***	0.28	-0.55 ***	0.01	-0.4 ***	–
VM	0	0.42 **	0.28	0.6 ***	0.19	0.07	-1.25 ***	-0.67 ***	-0.34	-1.4 ***	0.31	-0.52 ***	0.04	-0.37 ***	0.03

Table B.2: *Table showing the significance of pairwise comparisons of $\delta^{15}N$ differences between sites. Significance codes ($p < 0.001 =$***, $p < 0.01 =$ **, $p < 0.05 =$*) based on Tukey's Honestly Significant Difference family-wise comparison for the 95% confidence interval.*

Site-Site	ANAS	Castro dei Volsci	Catacombs	CD	CNM	Esanatoglia	Florence	Isola Sacra	MP	Naples	ODF	Pompeii	Palestrina	Rome	Velia
Castro dei Volsci	-2.02 **	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Catacombs	1.12	3.15 ***	–	–	–	–	–	–	–	–	–	–	–	–	–
Casale del Dolce	-1.55 **	0.47	-2.67 ***	–	–	–	–	–	–	–	–	–	–	–	–
CNM	-0.05	1.97 ***	-1.18	1.5 ***	–	–	–	–	–	–	–	–	–	–	–
Esanatoglia	-1.37	0.66	-2.49 ***	0.18	-1.31	–	–	–	–	–	–	–	–	–	–
Florence	2.59 ***	4.61 ***	1.47	4.14 ***	2.65 ***	3.96 ***	–	–	–	–	–	–	–	–	–
Isola Sacra	1.52 ***	3.54 ***	0.39	3.07 ***	1.57 ***	2.88 ***	-1.07	–	–	–	–	–	–	–	–
MP	1.01	3.03 ***	-0.11	2.56 ***	1.07	2.38 **	-1.58	-0.51	–	–	–	–	–	–	–
Naples	1.77 **	3.79 ***	0.65	3.32 ***	1.83 ***	3.14 ***	-0.82	0.26	0.76	–	–	–	–	–	–
ODF	-1.82 **	0.2	-2.94 ***	-0.27	-1.76 **	-0.45	-4.41 ***	-3.34 ***	-2.83 ***	-3.59 ***	–	–	–	–	–
Pompeii	0.83	2.85 ***	-0.29	2.38 ***	0.89	2.2 **	-1.76 **	-0.69	-0.18	-0.94	2.65 ***	–	–	–	–
Palestrina	0.44	2.46 **	-0.69	1.99 *	0.49	1.8	-2.15	-1.08	-0.57	-1.33	2.26 *	-0.39	–	–	–
Rome	1.57 **	3.59 ***	0.44	3.12 ***	1.62 ***	2.93 ***	-1.03	0.05	0.56	-0.21	3.39 ***	0.73	1.13	–	–
Velia	-0.85	1.17 *	-1.98 ***	0.7 *	-0.8	0.51	-3.44 ***	-2.37 ***	-1.86 ***	-2.62 ***	0.97	-1.68 ***	-1.29	-2.42 ***	–
VM	-1.74 ***	0.28	-2.86 ***	-0.19	-1.69 ***	-0.37	-4.33 ***	-3.26 ***	-2.75 ***	-3.51 ***	0.08	-2.57 ***	-2.18 **	-3.31 ***	-0.89 ***

B.2 Villamagna Analysis

B.2.1 Complex multivariate regression model for δ^{13}C

```
Call:
lm(formula = d13C ~ Phase + Sex + Grave.type + Location, data = vmadults2)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.55779 -0.21496 -0.01874  0.15406  1.10760 

Coefficients: (1 not defined because of singularities)
                            Estimate Std. Error t value Pr(>|t|)    
(Intercept)                -19.47552    0.25876 -75.263  < 2e-16 ***
PhaseEarly Medieval         -0.25357    0.22889  -1.108 0.270609    
PhaseLate Medieval          -0.25922    0.13929  -1.861 0.065707 .  
PhaseUnk                    -0.41014    0.28251  -1.452 0.149730    
SexF?                        0.29198    0.18096   1.613 0.109828    
SexM                         0.33115    0.08337   3.972 0.000135 ***
SexM?                       -0.06051    0.17448  -0.347 0.729494    
SexU                         0.36909    0.09427   3.915 0.000166 ***
Grave.typebuilt              0.14934    0.17523   0.852 0.396133    
Grave.typeearth              0.09892    0.14318   0.691 0.491242    
LocationChurchyard          -0.10878    0.14957  -0.727 0.468753    
LocationMonastery           -0.16354    0.20993  -0.779 0.437833    
LocationOther                     NA         NA      NA       NA    
LocationOutside Churchyard   0.43246    0.20294   2.131 0.035570 *  
LocationOutside Monastery    0.27080    0.25515   1.061 0.291112    
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1 

Residual standard error: 0.3267 on 99 degrees of freedom
Multiple R-squared: 0.3638,Adjusted R-squared: 0.2803 
F-statistic: 4.355 on 13 and 99 DF,  p-value: 9.142e-06
```

B.2.2 Simple multivariate regression model for δ^{13}C

```
Call:
lm(formula = d13C ~ Phase2 + Sex2 + Location3, data = vmadults2)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.58393 -0.20389 -0.03393  0.15656  1.16050 

Coefficients:
                             Estimate Std. Error  t value Pr(>|t|)    
(Intercept)                 -19.36045    0.09801 -197.526  < 2e-16 ***
Phase2Late Medieval          -0.33456    0.08571   -3.904 0.000165 ***
Sex2M                         0.24387    0.07575    3.219 0.001698 ** 
Sex2U                         0.33894    0.09146    3.706 0.000334 ***
Location3Outside Churchyard   0.46890    0.14224    3.297 0.001325 ** 
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1 

Residual standard error: 0.3351 on 108 degrees of freedom
Multiple R-squared: 0.2696,Adjusted R-squared: 0.2426 
F-statistic: 9.966 on 4 and 108 DF,  p-value: 6.671e-07
```

B.2.3 Comparison of simple and complex multivariate regression models for δ^{13}C

```
Analysis of Variance Table

Model 1: d13C ~ Phase + Sex + Grave.type + Location
Model 2: d13C ~ Phase2 + Sex2 + Location3
```

```
  Res.Df    RSS Df Sum of Sq      F Pr(>F)
1     99 10.564
2    108 12.129 -9   -1.5648 1.6295 0.1171
```

B.2.4 Complex multivariate regression model for δ^{15}N

```
Call:
lm(formula = d15N ~ Phase + Sex + Grave.type + Location, data = vmadults2)

Residuals:
    Min      1Q  Median      3Q     Max
-2.5237 -0.5321 -0.0354  0.2821  5.0730

Coefficients: (1 not defined because of singularities)
                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                 6.25361    0.81439   7.679 1.16e-11 ***
PhaseEarly Medieval         0.34988    0.72036   0.486   0.6283
PhaseLate Medieval          0.82225    0.43837   1.876   0.0636 .
PhaseUnk                    0.53450    0.88913   0.601   0.5491
SexF?                       0.85820    0.56954   1.507   0.1350
SexM                        0.59872    0.26239   2.282   0.0246 *
SexM?                      -0.01480    0.54913  -0.027   0.9786
SexU                        0.60811    0.29669   2.050   0.0430 *
Grave.typebuilt             0.43999    0.55148   0.798   0.4269
Grave.typeearth             0.24346    0.45063   0.540   0.5902
LocationChurchyard         -0.06707    0.47073  -0.142   0.8870
LocationMonastery           1.72381    0.66070   2.609   0.0105 *
LocationOther                    NA         NA      NA       NA
LocationOutside Churchyard  0.02259    0.63870   0.035   0.9719
LocationOutside Monastery   2.09673    0.80302   2.611   0.0104 *
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1

Residual standard error: 1.028 on 99 degrees of freedom
Multiple R-squared: 0.2205,Adjusted R-squared: 0.1181
F-statistic: 2.154 on 13 and 99 DF,  p-value: 0.0171
```

B.2.5 Simple multivariate regression model for δ^{15}N

```
Call:
lm(formula = d15N ~ Phase2 + Sex2 + Location3, data = vmadults2)

Residuals:
    Min      1Q  Median      3Q     Max
-2.5124 -0.4982 -0.0301  0.3451  5.0843

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)
(Intercept)               6.8634     0.3501  19.602  < 2e-16 ***
Phase2Late Medieval       0.5366     0.3223   1.665   0.0988 .
Sex2M                     0.3815     0.2274   1.678   0.0963 .
Sex2U                     0.4490     0.2751   1.632   0.1056
Location3Near Monastery   1.7588     0.4229   4.159 6.43e-05 ***
---
Signif. codes:  0 *** 0.001 ** 0.01 * 0.05 . 0.1   1

Residual standard error: 1.01 on 108 degrees of freedom
Multiple R-squared: 0.1796,Adjusted R-squared: 0.1492
F-statistic: 5.912 on 4 and 108 DF,  p-value: 0.0002432
```

B.2.6 Comparison of simple and complex multivariate regression models for δ^{15}N

```
Analysis of Variance Table
```

```
Model 1: d15N ~ Phase + Sex + Grave.type + Location
Model 2: d15N ~ Phase2 + Sex2 + Location3
  Res.Df    RSS Df Sum of Sq      F Pr(>F)
1     99 104.63
2    108 110.12 -9   -5.4822 0.5763 0.8136
```

B.3 Italy: Statistical Models

B.3.1 Adults

```
Linear mixed-effects model fit by REML
 Data: italy
       AIC      BIC    logLik
  663.3811 699.3794 -323.6905

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.4368467 0.3731684

Fixed effects: d13C ~ Datecode + CI + Sex
                 Value  Std.Error  DF   t-value p-value
(Intercept) -18.766066 0.29921095 652 -62.71851  0.0000
DatecodeR    -0.384868 0.25849325  13  -1.48889  0.1604
DatecodeLM    0.247879 0.14588954 652   1.69909  0.0898
CII          -0.574973 0.24794050  13  -2.31900  0.0373
SexM          0.145363 0.04778173 652   3.04223  0.0024
SexU          0.092775 0.05349512 652   1.73427  0.0833
 Correlation:
           (Intr) DatcdR DtcdLM CII    SexM
DatecodeR  -0.732
DatecodeLM -0.371  0.390
CII        -0.702  0.253  0.059
SexM       -0.109  0.003  0.004 -0.007
SexU       -0.150  0.014  0.034 -0.040  0.636

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.23145841 -0.60291913 -0.08111456  0.49686019  4.49383030

Number of Observations: 671
Number of Groups: 16

Linear mixed-effects model fit by REML
 Data: italy
      AIC      BIC   logLik
  2224.24 2260.238 -1104.12

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.426238 1.206436

Fixed effects: d15N ~ Datecode + CI + Sex
                Value Std.Error  DF   t-value p-value
(Intercept)  9.687255 0.9752479 652  9.933120  0.0000
DatecodeR    0.152762 0.8425103  13  0.181318  0.8589
DatecodeLM   0.632245 0.4722330 652  1.338842  0.1811
CII         -0.806639 0.8091824  13 -0.996857  0.3370
SexM         0.408277 0.1544765 652  2.642972  0.0084
SexU         0.186163 0.1729580 652  1.076346  0.2822
 Correlation:
           (Intr) DatcdR DtcdLM CII    SexM
DatecodeR  -0.732
```

```
DatecodeLM -0.368  0.387
CII        -0.703  0.253  0.058
SexM       -0.108  0.003  0.004 -0.007
SexU       -0.149  0.013  0.034 -0.039  0.636

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-2.8753754 -0.6060231 -0.1042030  0.4401755  4.3604423

Number of Observations: 671
Number of Groups: 16
```

Model recentred for Roman comparison:

```
Linear mixed-effects model fit by REML
 Data: italy
       AIC      BIC    logLik
  663.3811 699.3794 -323.6905

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.4368467 0.3731684

Fixed effects: d13C ~ Datecode + CI + Sex
                 Value  Std.Error  DF   t-value p-value
(Intercept) -19.150933 0.20753765 651 -92.27691  0.0000
DatecodeEM    0.384868 0.25849325 651   1.48889  0.1370
DatecodeLM    0.632747 0.24225306 651   2.61193  0.0092
CII          -0.574973 0.24794050  14  -2.31900  0.0360
SexM          0.145363 0.04778173 651   3.04223  0.0024
SexU          0.092775 0.05349512 651   1.73427  0.0833
 Correlation:
           (Intr) DtcdEM DtcdLM CII    SexM
DatecodeEM -0.190
DatecodeLM -0.232  0.832
CII        -0.697 -0.253 -0.234
SexM       -0.154 -0.003 -0.001 -0.007
SexU       -0.199 -0.014  0.006 -0.040  0.636

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.23145841 -0.60291913 -0.08111456  0.49686019  4.49383030

Number of Observations: 671
Number of Groups: 16


Linear mixed-effects model fit by REML
 Data: italy
      AIC      BIC   logLik
  2224.24 2260.238 -1104.12

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.426238 1.206436

Fixed effects: d15N ~ Datecode + CI + Sex
                Value Std.Error  DF   t-value p-value
(Intercept)  9.840017 0.6771664 651 14.531165  0.0000
DatecodeEM  -0.152762 0.8425103 651 -0.181318  0.8562
DatecodeLM   0.479483 0.7903714 651  0.606656  0.5443
CII         -0.806639 0.8091824  14 -0.996857  0.3358
SexM         0.408277 0.1544765 651  2.642972  0.0084
SexU         0.186163 0.1729580 651  1.076346  0.2822
 Correlation:
```

```
           (Intr) DtcdEM DtcdLM CII    SexM 
DatecodeEM -0.190                           
DatecodeLM -0.232  0.835                    
CII        -0.698 -0.253 -0.234             
SexM       -0.153 -0.003 -0.001 -0.007      
SexU       -0.198 -0.013  0.006 -0.039  0.636

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max 
-2.8753754 -0.6060231 -0.1042030  0.4401755  4.3604423 

Number of Observations: 671
Number of Groups: 16 
```

B.3.2 Italy: Models, Florence and Naples removed

```
Linear mixed-effects model fit by REML
 Data: italy.rm 
       AIC      BIC    logLik
  585.9317 621.5101 -284.9658

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.3300688 0.3627378

Fixed effects: d13C ~ Datecode + CI + Sex 
                 Value  Std.Error  DF    t-value p-value
(Intercept) -19.251312 0.17189483 619 -111.99471  0.0000
DatecodeEM    0.029294 0.23254367 619    0.12597  0.8998
DatecodeLM    0.223617 0.23208751 619    0.96350  0.3357
CII          -0.401992 0.21988700  12   -1.82818  0.0925
SexM          0.145160 0.04644309 619    3.12555  0.0019
SexU          0.088775 0.05196883 619    1.70824  0.0881
 Correlation: 
           (Intr) DtcdEM DtcdLM CII    SexM 
DatecodeEM -0.002                           
DatecodeLM -0.006  0.819                    
CII        -0.731 -0.391 -0.394             
SexM       -0.178  0.000  0.003 -0.011      
SexU       -0.215  0.011  0.037 -0.069  0.636

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max 
-3.32618694 -0.60961630 -0.08963194  0.47816845  4.64289587 

Number of Observations: 637
Number of Groups: 14 


Linear mixed-effects model fit by REML
 Data: italy.rm 
       AIC      BIC    logLik
  2121.557 2157.136 -1052.779

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.285124 1.221892

Fixed effects: d15N ~ Datecode + CI + Sex 
                Value Std.Error  DF   t-value p-value
(Intercept)  9.654479 0.6627290 619 14.567763  0.0000
DatecodeEM  -0.990737 0.8877564 619 -1.116001  0.2649
DatecodeLM  -0.498352 0.8876069 619 -0.561456  0.5747
CII         -0.487802 0.8496438  12 -0.574125  0.5765
```

```
SexM         0.407972 0.1564529 619  2.607637  0.0093
SexU         0.179784 0.1752245 619  1.026022  0.3053
 Correlation:
           (Intr) DtcdEM DtcdLM CII    SexM
DatecodeEM -0.001
DatecodeLM -0.005  0.854
CII        -0.741 -0.393 -0.395
SexM       -0.156  0.000  0.003 -0.010
SexU       -0.188  0.010  0.032 -0.060  0.636

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.83170428 -0.60587154 -0.09737091  0.45091016  4.30454703

Number of Observations: 637
Number of Groups: 14
```

B.3.3 Italy: Models - Juveniles

```
Linear mixed-effects model fit by REML
 Data: italy.j
      AIC    BIC   logLik
  730.398 771.76 -356.199

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.3931146 0.3741551

Fixed effects: d13C ~ Datecode + CI + Sex + Agecat
                 Value  Std.Error  DF   t-value p-value
(Intercept) -18.621039 0.26962462 719 -69.06283  0.0000
DatecodeLM    0.253536 0.14053866 719   1.80403  0.0716
DatecodeR    -0.539515 0.23171811  13  -2.32832  0.0367
CII          -0.684220 0.22941681  13  -2.98243  0.0106
SexM          0.133768 0.04679121 719   2.85882  0.0044
SexU          0.070068 0.05081763 719   1.37882  0.1684
AgecatJ      -0.155178 0.05563724 719  -2.78910  0.0054
 Correlation:
           (Intr) DtcdLM DatcdR CII    SexM   SexU
DatecodeLM -0.364
DatecodeR  -0.730  0.376
CII        -0.747  0.085  0.334
SexM       -0.117  0.003  0.002 -0.006
SexU       -0.157  0.024  0.016 -0.037  0.641
AgecatJ     0.055 -0.104 -0.053 -0.015  0.005 -0.161

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.23537647 -0.60091899 -0.08996695  0.49594356  4.47123840

Number of Observations: 739
Number of Groups: 16


Linear mixed-effects model fit by REML
 Data: italy.j
       AIC      BIC    logLik
  2433.072 2474.434 -1207.536

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.429136  1.19454
```

```
Fixed effects: d15N ~ Datecode + CI + Sex + Agecat
                Value Std.Error  DF   t-value p-value
(Intercept) 10.199737 0.9608737 719 10.615065  0.0000
DatecodeLM   0.509152 0.4585899 719  1.110255  0.2673
DatecodeR   -0.347115 0.8262971  13 -0.420085  0.6813
CII         -0.978797 0.8297353  13 -1.179650  0.2593
SexM         0.355041 0.1493921 719  2.376572  0.0177
SexU         0.098139 0.1623570 719  0.604466  0.5457
AgecatJ     -0.088646 0.1777823 719 -0.498623  0.6182
 Correlation:
           (Intr) DtcdLM DatcdR CII    SexM   SexU
DatecodeLM -0.333
DatecodeR  -0.724  0.343
CII        -0.755  0.077  0.332
SexM       -0.105  0.003  0.002 -0.005
SexU       -0.141  0.024  0.014 -0.033  0.641
AgecatJ     0.051 -0.106 -0.049 -0.014  0.005 -0.161

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.90995253 -0.60667165 -0.09838835  0.42707890  4.42218106

Number of Observations: 739
Number of Groups: 16
```

B.3.4 Italy: Models - Rural/Urban

Rural/Urban replacing Coastal/Inland:

```
Linear mixed-effects model fit by REML
 Data: italy
       AIC      BIC    logLik
  659.9085 695.9068 -321.9543

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.3838427 0.3730601

Fixed effects: d13C ~ Datecode + RU + Sex
                 Value  Std.Error  DF    t-value p-value
(Intercept) -19.276762 0.14775688 651 -130.46270  0.0000
DatecodeEM    0.411102 0.23287370 651    1.76534  0.0780
DatecodeLM    0.615125 0.21157023 651    2.90743  0.0038
RUR          -0.696061 0.21157206  14   -3.28995  0.0054
SexM          0.144990 0.04776458 651    3.03551  0.0025
SexU          0.088661 0.05337615 651    1.66106  0.0972
 Correlation:
           (Intr) DtcdEM DtcdLM RUR    SexM
DatecodeEM -0.333
DatecodeLM -0.431  0.789
RUR        -0.431 -0.257 -0.152
SexM       -0.222 -0.004 -0.002 -0.002
SexU       -0.317 -0.025 -0.004 -0.004  0.637

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.23521904 -0.60492837 -0.07540037  0.51391865  4.51190140

Number of Observations: 671
Number of Groups: 16


Linear mixed-effects model fit by REML
 Data: italy
       AIC      BIC    logLik
  2210.787 2246.786 -1097.394
```

```
Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    0.829233 1.205872

Fixed effects: d15N ~ Datecode + RU + Sex
                Value Std.Error  DF   t-value p-value
(Intercept) 10.052622 0.3468848 651 28.979715  0.0000
DatecodeEM   0.191506 0.5630649 651  0.340113  0.7339
DatecodeLM   0.705702 0.4769211 651  1.479704  0.1394
RUR         -2.390838 0.4769045  14 -5.013243  0.0002
SexM         0.414755 0.1543551 651  2.687021  0.0074
SexU         0.216788 0.1714924 651  1.264124  0.2066
 Correlation:
           (Intr) DtcdEM DtcdLM RUR    SexM
DatecodeEM -0.258
DatecodeLM -0.413  0.654
RUR        -0.414 -0.293 -0.119
SexM       -0.305 -0.005 -0.003 -0.003
SexU       -0.431 -0.034 -0.006 -0.006  0.639

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.90691918 -0.61008934 -0.09192387  0.44703596  4.34395137

Number of Observations: 671
Number of Groups: 16
```

Rural/Urban and Coastal/Inland:

```
Linear mixed-effects model fit by REML
 Data: italy
       AIC      BIC    logLik
  661.5796 702.0641 -321.7898

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.3788183 0.3730787

Fixed effects: d13C ~ Datecode + RU + CI + Sex
                 Value  Std.Error  DF    t-value p-value
(Intercept) -19.155415 0.18180541 651 -105.36218  0.0000
DatecodeEM    0.447390 0.23289027 651    1.92103  0.0552
DatecodeLM    0.658876 0.21258814 651    3.09931  0.0020
RUR          -0.557761 0.24254189  13   -2.29965  0.0387
CII          -0.281727 0.25106220  13   -1.12214  0.2821
SexM          0.145420 0.04776814 651    3.04429  0.0024
SexU          0.091727 0.05343979 651    1.71646  0.0866
 Correlation:
           (Intr) DtcdEM DtcdLM RUR    CII    SexM
DatecodeEM -0.179
DatecodeLM -0.232  0.790
RUR         0.004 -0.148 -0.035
CII        -0.595 -0.143 -0.182 -0.507
SexM       -0.176 -0.003 -0.001  0.002 -0.008
SexU       -0.227 -0.018  0.006  0.023 -0.051  0.636

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.23277071 -0.60797042 -0.07365766  0.51191703  4.50519558

Number of Observations: 671
Number of Groups: 16

Linear mixed-effects model fit by REML
```

```
 Data: italy
       AIC      BIC    logLik
  2210.878 2251.362 -1096.439

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:   0.8212042 1.205875

Fixed effects: d15N ~ Datecode + RU + CI + Sex
                Value Std.Error  DF   t-value p-value
(Intercept)  9.800434 0.4127354 651 23.745079  0.0000
DatecodeEM   0.110435 0.5640259 651  0.195797  0.8448
DatecodeLM   0.600799 0.4824650 651  1.245270  0.2135
RUR         -2.705983 0.5526379  13 -4.896484  0.0003
CII          0.622720 0.5641574  13  1.103805  0.2897
SexM         0.413062 0.1543637 651  2.675901  0.0076
SexU         0.203872 0.1719212 651  1.185848  0.2361
 Correlation:
           (Intr) DtcdEM DtcdLM RUR    CII    SexM
DatecodeEM -0.142
DatecodeLM -0.229  0.658
RUR        -0.010 -0.184  0.004
CII        -0.551 -0.127 -0.198 -0.517
SexM       -0.250 -0.004 -0.001  0.003 -0.011
SexU       -0.320 -0.024  0.009  0.033 -0.073  0.638

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.95158089 -0.61629898 -0.09381835  0.44642321  4.34756065

Number of Observations: 671
Number of Groups: 16
```

B.4 Meta-analysis: Fauna

B.4.1 Meta-analysis: Fauna - by species

Cattle:

```
Linear mixed-effects model fit by REML
 Data: bos
       AIC     BIC    logLik
  435.4385 462.474 -208.7192

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:    0.555132 0.8314371

Fixed effects: d13C ~ Datecode + Loccode + CI
                 Value Std.Error  DF   t-value p-value
(Intercept) -21.704872 0.4597723 117 -47.20788  0.0000
DatecodeLM    0.245151 0.3305999 117   0.74153  0.4599
DatecodeR     0.084872 0.3585046 117   0.23674  0.8133
LoccodeMed    1.694875 0.4697935  32   3.60770  0.0010
LoccodeNE    -0.340676 0.4899366  32  -0.69535  0.4919
LoccodeUK    -0.252929 0.4292955  32  -0.58917  0.5599
CII           0.071428 0.3089130  32   0.23122  0.8186
 Correlation:
           (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.216
```

```
DatecodeR  -0.244  0.736
LoccodeMed -0.651 -0.442 -0.312
LoccodeNE  -0.486 -0.430 -0.340  0.712
LoccodeUK  -0.483 -0.360 -0.362  0.701  0.666
CII        -0.673 -0.019  0.029  0.406  0.192  0.081

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.50885881 -0.35649180 -0.02457814  0.33112375  4.95805637

Number of Observations: 156
Number of Groups: 37

Linear mixed-effects model fit by REML
 Data: bos
      AIC      BIC    logLik
  583.207 610.2425 -282.6035

Random effects:
 Formula: ˜1 | Site
        (Intercept) Residual
StdDev:   0.9261217 1.362378

Fixed effects: d15N ˜ Datecode + Loccode + CI
                Value Std.Error  DF   t-value p-value
(Intercept)  5.440532 0.7618890 117  7.140845  0.0000
DatecodeLM   0.449715 0.5443065 117  0.826217  0.4104
DatecodeR    1.059668 0.5907405 117  1.793796  0.0754
LoccodeMed   0.209805 0.7773830  32  0.269887  0.7890
LoccodeNE    0.070312 0.8096024  32  0.086847  0.9313
LoccodeUK   -0.305230 0.7110750  32 -0.429252  0.6706
CII          0.079825 0.5115094  32  0.156057  0.8770
 Correlation:
           (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.216
DatecodeR  -0.244  0.736
LoccodeMed -0.654 -0.439 -0.309
LoccodeNE  -0.489 -0.427 -0.337  0.712
LoccodeUK  -0.485 -0.356 -0.359  0.700  0.666
CII        -0.672 -0.018  0.029  0.407  0.192  0.081

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.89875857 -0.54576553  0.07189447  0.50135918  2.76532993

Number of Observations: 156
Number of Groups: 37
```

Sheep/goat:

```
Linear mixed-effects model fit by REML
 Data: ovicaprid
       AIC      BIC    logLik
  448.4645 478.3276 -215.2322

Random effects:
 Formula: ˜1 | Site
        (Intercept)  Residual
StdDev:   0.4773929 0.5929648

Fixed effects: d13C ˜ Datecode + Loccode + CI
                 Value Std.Error  DF   t-value p-value
(Intercept) -21.759609 0.3711835 172 -58.62225  0.0000
DatecodeLM    0.010318 0.1888253 172   0.05464  0.9565
DatecodeR     0.020832 0.2314223 172   0.09002  0.9284
LoccodeMed    1.819858 0.3523471  32   5.16496  0.0000
LoccodeNE    -0.124378 0.3784786  32  -0.32863  0.7446
```

```
LoccodeUK    -0.182358 0.3458302  32  -0.52730  0.6016
CII           0.347921 0.2322983  32   1.49773  0.1440
 Correlation:
          (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.210
DatecodeR  -0.243  0.660
LoccodeMed -0.776 -0.281 -0.140
LoccodeNE  -0.545 -0.241 -0.236  0.673
LoccodeUK  -0.589 -0.200 -0.188  0.704  0.641
CII        -0.628 -0.015  0.024  0.409  0.118  0.089

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.41038419 -0.56293747 -0.08673344  0.43244053  5.47097126

Number of Observations: 211
Number of Groups: 37

Linear mixed-effects model fit by REML
 Data: ovicaprid
       AIC      BIC    logLik
  859.3565 889.2195 -420.6782

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:     1.02281 1.666142

Fixed effects: d15N ~ Datecode + Loccode + CI
                Value Std.Error  DF   t-value p-value
(Intercept)  5.902310 0.8666286 172  6.810657  0.0000
DatecodeLM   0.355330 0.5091198 172  0.697930  0.4862
DatecodeR    1.066733 0.6059143 172  1.760535  0.0801
LoccodeMed  -0.484427 0.8287506  32 -0.584526  0.5630
LoccodeNE    0.151926 0.9191271  32  0.165293  0.8698
LoccodeUK   -0.167341 0.8075785  32 -0.207213  0.8372
CII          0.073692 0.5403578  32  0.136377  0.8924
 Correlation:
          (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.235
DatecodeR  -0.263  0.682
LoccodeMed -0.740 -0.329 -0.178
LoccodeNE  -0.494 -0.273 -0.271  0.656
LoccodeUK  -0.562 -0.244 -0.230  0.713  0.630
CII        -0.623 -0.019  0.012  0.405  0.111  0.090

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-1.9214574 -0.6138274 -0.1071116  0.5369456  3.4069316

Number of Observations: 211
Number of Groups: 37
```

Pig:

```
Linear mixed-effects model fit by REML
 Data: sus
       AIC      BIC    logLik
  324.4945 351.4694 -153.2472

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:   0.5678744 0.547073

Fixed effects: d13C ~ Datecode + Loccode + CI
                 Value Std.Error  DF   t-value p-value
```

```
(Intercept) -21.288759 0.4222937 116 -50.41222  0.0000
DatecodeLM    0.262436 0.2117215 116   1.23954  0.2176
DatecodeR    -0.219816 0.2230157 116  -0.98565  0.3264
LoccodeMed    1.177567 0.4161699  32   2.82953  0.0080
LoccodeNE    -0.300898 0.4161085  32  -0.72312  0.4749
LoccodeUK    -0.156528 0.3964975  32  -0.39478  0.6956
CII           0.088454 0.2696868  32   0.32799  0.7451
 Correlation:
           (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.184
DatecodeR  -0.231  0.767
LoccodeMed -0.785 -0.268 -0.174
LoccodeNE  -0.659 -0.278 -0.210  0.742
LoccodeUK  -0.587 -0.216 -0.197  0.679  0.667
CII        -0.638 -0.037  0.025  0.448  0.261  0.092

Standardized Within-Group Residuals:
         Min           Q1          Med           Q3          Max
-1.634159340 -0.681598526 -0.002050748  0.507388535  3.590361730

Number of Observations: 155
Number of Groups: 37

Linear mixed-effects model fit by REML
 Data: sus
       AIC      BIC    logLik
  606.2214 633.1963 -294.1107

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:      1.5939 1.396616

Fixed effects: d15N ~ Datecode + Loccode + CI
                Value Std.Error  DF   t-value p-value
(Intercept)  6.537778 1.1598072 116  5.636952  0.0000
DatecodeLM   0.246396 0.5479549 116  0.449665  0.6538
DatecodeR   -0.129967 0.5786560 116 -0.224601  0.8227
LoccodeMed  -0.015784 1.1409101  32 -0.013834  0.9890
LoccodeNE    0.433062 1.1382089  32  0.380477  0.7061
LoccodeUK    0.861010 1.0921120  32  0.788390  0.4363
CII          0.258486 0.7368718  32  0.350789  0.7280
 Correlation:
           (Intr) DtcdLM DatcdR LccdMd LccdNE LccdUK
DatecodeLM -0.176
DatecodeR  -0.221  0.764
LoccodeMed -0.797 -0.251 -0.161
LoccodeNE  -0.675 -0.260 -0.195  0.745
LoccodeUK  -0.599 -0.198 -0.182  0.680  0.669
CII        -0.635 -0.035  0.025  0.445  0.260  0.090

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.41092364 -0.63730354  0.07888651  0.66294446  2.19371549

Number of Observations: 155
Number of Groups: 37
```

B.4.2 Meta-analysis: Fauna - Mediterranean

```
Linear mixed-effects model fit by REML
 Data: med
       AIC      BIC    logLik
  613.8996 640.7145 -298.9498

Random effects:
```

```
 Formula: ~1 | Site
       (Intercept)  Residual
StdDev:   0.7524448 0.8839018

Fixed effects: d13C ~ Datecode + CI + Species
                      Value Std.Error  DF   t-value p-value
(Intercept)      -20.017093 0.4271420 197 -46.86285  0.0000
DatecodeLM         0.188785 0.3225689 197   0.58526  0.5590
DatecodeR          0.110816 0.4804679 197   0.23064  0.8178
CII                0.426719 0.4254242  14   1.00304  0.3329
Speciesovicaprid  -0.183566 0.1527071 197  -1.20208  0.2308
Speciessus        -0.164341 0.1862591 197  -0.88232  0.3787
 Correlation:
                 (Intr) DtcdLM DatcdR CII    Spcsvc
DatecodeLM       -0.723
DatecodeR        -0.646  0.652
CII              -0.380 -0.037  0.144
Speciesovicaprid -0.248  0.007 -0.021 -0.008
Speciessus       -0.230  0.045 -0.029 -0.001  0.561

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-2.1235223 -0.5430317 -0.1122164  0.3836681  4.9807297

Number of Observations: 217
Number of Groups: 16
> summary(lme(d15N ~ Datecode + CI + Species , random = ~1 | Site, data=med))
Linear mixed-effects model fit by REML
 Data: med
       AIC      BIC    logLik
  920.1313 946.9461 -452.0656

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.375093 1.839423

Fixed effects: d15N ~ Datecode + CI + Species
                     Value Std.Error  DF   t-value p-value
(Intercept)       5.118293 0.8514319 197  6.011394  0.0000
DatecodeLM        0.842864 0.6691414 197  1.259621  0.2093
DatecodeR         1.340625 0.9694112 197  1.382927  0.1683
CII               0.916284 0.7928784  14  1.155642  0.2672
Speciesovicaprid -0.601864 0.3173416 197 -1.896582  0.0593
Speciessus        0.306472 0.3871058 197  0.791702  0.4295
 Correlation:
                 (Intr) DtcdLM DatcdR CII    Spcsvc
DatecodeLM       -0.751
DatecodeR        -0.671  0.668
CII              -0.352 -0.042  0.145
Speciesovicaprid -0.262  0.007 -0.014 -0.006
Speciessus       -0.240  0.044 -0.027  0.000  0.561

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.53353243 -0.61450217 -0.04503088  0.61971198  3.28602311

Number of Observations: 217
Number of Groups: 16
```

B.5 Meta-analysis: Humans

B.5.1 Juvenile comparison

```
data.j1 <- data[data$Agecat=="J",]
data.j <- merge(data.a, data.j1, all=TRUE)
```

```
summary(lme(d13C ~ Datecode + Loccode + CI + Sex + Agecat, random = ~1 | Site, data=data.j))

Linear mixed-effects model fit by REML
 Data: data.j
       AIC      BIC    logLik
  8108.625 8180.617 -4042.313
Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.5672527 0.9003682
Fixed effects: d13C ~ Datecode + Loccode + CI + Sex + Agecat
                 Value  Std.Error   DF   t-value p-value
(Intercept) -20.226295 0.20700888 2884 -97.70738  0.0000
DatecodeLM    0.551521 0.11075249 2884   4.97976  0.0000
DatecodeR     0.193035 0.12735066 2884   1.51578  0.1297
LoccodeUK     0.417549 0.19933943   95   2.09466  0.0389
LoccodeCE     0.684415 0.29802255   95   2.29652  0.0238
LoccodeMed    1.202180 0.18581319   95   6.46983  0.0000
CII          -0.346489 0.14263404   95  -2.42922  0.0170
SexM          0.131969 0.04228566 2884   3.12090  0.0018
SexU          0.033174 0.05902016 2884   0.56208  0.5741
AgecatJ       0.037927 0.07343578 2884   0.51647  0.6056
 Correlation:
           (Intr) DtcdLM DatcdR LccdUK LccdCE LccdMd CII    SexM   SexU
DatecodeLM -0.445
DatecodeR  -0.470  0.567
LoccodeUK  -0.641  0.159  0.214
LoccodeCE  -0.412  0.134  0.167  0.492
LoccodeMed -0.692 -0.026  0.101  0.671  0.443
CII        -0.452  0.162  0.133 -0.147 -0.180  0.074
SexM       -0.097 -0.028 -0.034 -0.016 -0.001  0.000 -0.007
SexU       -0.086  0.060  0.008  0.019  0.029 -0.061 -0.072  0.433
AgecatJ    -0.022 -0.013  0.017  0.007  0.007  0.046  0.042 -0.021 -0.461
Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-4.03928042 -0.30128772 -0.03585015  0.24762594 43.42851114
Number of Observations: 2989
Number of Groups: 100
```

```
summary(lme(d15N ~ Datecode + Loccode + CI + Sex + Agecat, random = ~1 | Site, data=data.j))

Linear mixed-effects model fit by REML
 Data: data.j
       AIC      BIC    logLik
  8916.272 8988.264 -4446.136
Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:    1.122077 1.015102
Fixed effects: d15N ~ Datecode + Loccode + CI + Sex + Agecat
                Value Std.Error   DF   t-value p-value
(Intercept) 10.526032 0.3474918 2884 30.291456  0.0000
DatecodeLM   0.791043 0.1442711 2884  5.483030  0.0000
DatecodeR    0.507317 0.1715899 2884  2.956567  0.0031
LoccodeUK    0.051383 0.3581525   95  0.143468  0.8862
LoccodeCE   -0.861160 0.5569773   95 -1.546132  0.1254
LoccodeMed  -0.882183 0.3341037   95 -2.640448  0.0097
CII         -0.660079 0.2622695   95 -2.516797  0.0135
SexM         0.313927 0.0478368 2884  6.562467  0.0000
SexU         0.104706 0.0678454 2884  1.543296  0.1229
AgecatJ     -0.046455 0.0836647 2884 -0.555249  0.5788
 Correlation:
           (Intr) DtcdLM DatcdR LccdUK LccdCE LccdMd CII    SexM   SexU
DatecodeLM -0.339
DatecodeR  -0.373  0.551
LoccodeUK  -0.618  0.103  0.161
```

```
LoccodeCE  -0.366  0.082  0.114  0.447
LoccodeMed -0.723 -0.029  0.083  0.653  0.413
CII        -0.469  0.126  0.100 -0.157 -0.187  0.077
SexM       -0.065 -0.029 -0.031 -0.010  0.000  0.001 -0.006
SexU       -0.061  0.041  0.017  0.017  0.021 -0.033 -0.049  0.429
AgecatJ    -0.011 -0.001  0.008  0.000  0.000  0.023  0.030 -0.023 -0.470
Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-4.66539233 -0.54528488 -0.05007606  0.51683525  6.14164693
Number of Observations: 2989
Number of Groups: 100
```

B.5.2 Meta-analysis Mediterranean humans and geographical parameters

```
Linear mixed-effects model fit by REML
 Data: med
      AIC      BIC    logLik
  1916.66 1971.694 -947.3302

Random effects:
 Formula: ~1 | Site
        (Intercept)  Residual
StdDev:   0.5975341 0.5304954

Fixed effects: d13C ~ Datecode + CI + Sex + Latitude + Longitude + log(masl)
                 Value Std.Error   DF   t-value p-value
(Intercept) -14.787028 2.7452047 1060 -5.386494  0.0000
DatecodeEM   -0.039051 0.2795857 1060 -0.139676  0.8889
DatecodeLM    0.613108 0.2644902 1060  2.318074  0.0206
CII          -0.360883 0.3470439   40 -1.039878  0.3046
SexM          0.110962 0.0440802 1060  2.517264  0.0120
SexU          0.047171 0.0547910 1060  0.860919  0.3895
Latitude     -0.084426 0.0662182   40 -1.274965  0.2097
Longitude    -0.052794 0.0113068   40 -4.669201  0.0000
log(masl)    -0.047934 0.1073664 1060 -0.446450  0.6554
 Correlation:
           (Intr) DtcdEM DtcdLM CII    SexM   SexU   Latitd Longtd
DatecodeEM -0.296
DatecodeLM -0.314  0.913
CII         0.501  0.191  0.230
SexM       -0.003  0.008  0.000 -0.017
SexU        0.062  0.001  0.030 -0.029  0.528
Latitude   -0.992  0.287  0.302 -0.469 -0.007 -0.079
Longitude  -0.499  0.227  0.230 -0.156 -0.016 -0.072  0.461
log(masl)  -0.150 -0.438 -0.457 -0.721  0.013  0.043  0.068 -0.001

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-2.9464688 -0.5059949 -0.0854216  0.3653261  9.6301638

Number of Observations: 1109
Number of Groups: 44

Linear mixed-effects model fit by REML
 Data: med
       AIC      BIC    logLik
  3598.905 3653.938 -1788.452

Random effects:
 Formula: ~1 | Site
        (Intercept) Residual
StdDev:   0.9779828 1.149603

Fixed effects: d15N ~ Datecode + CI + Sex + Latitude + Longitude + log(masl)
                Value Std.Error   DF   t-value p-value
```

```
(Intercept) 16.609549  4.568945 1060  3.635314  0.0003
DatecodeEM   0.369100  0.480643 1060  0.767930  0.4427
DatecodeLM   0.432693  0.441817 1060  0.979347  0.3276
CII          0.273084  0.579304   40  0.471400  0.6399
SexM         0.237527  0.095418 1060  2.489341  0.0130
SexU         0.014579  0.118247 1060  0.123294  0.9019
Latitude    -0.101468  0.110274   40 -0.920141  0.3630
Longitude   -0.084875  0.019045   40 -4.456568  0.0001
log(masl)   -0.493654  0.179294 1060 -2.753315  0.0060
 Correlation:
           (Intr) DtcdEM DtcdLM CII    SexM   SexU   Latitd Longtd
DatecodeEM -0.285
DatecodeLM -0.311  0.869
CII         0.495  0.173  0.230
SexM       -0.004  0.008  0.001 -0.020
SexU        0.079  0.000  0.039 -0.038  0.529
Latitude   -0.992  0.277  0.299 -0.463 -0.009 -0.101
Longitude  -0.498  0.220  0.225 -0.154 -0.021 -0.090  0.459
log(masl)  -0.147 -0.427 -0.456 -0.719  0.016  0.057  0.064  0.000

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.00818266 -0.57551981 -0.06245838  0.47830796  5.37614911

Number of Observations: 1109
Number of Groups: 44
```

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