Pig Husbandry at Kastro Kallithea: An Isotopic Study of Pig Husbandry in Hellenistic Thessaly

by

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Abstract

The goal of this study was to determine the pig husbandry practice(s) employed at the Hellenistic city of Kastro Kallithea. Kastro Kallithea was occupied from the 4th to 2nd centuries BCE. One of the primary goals of the Kastro Kallithea archaeological project was to examine the domestic economy of the site. This study adds to previous and ongoing research via a bioarchaeological approach. Excavations at the site were completed prior to the outset of this research. Bone samples were gathered from 30 pigs and 6 sheep and goats. Stable carbon and nitrogen isotopes from bone collagen were used to reconstruct the dietary composition of the animals. The results show a primarily C_3 diet for the pigs, with $\delta^{15}N$ values elevated over the sheep/goat remains sampled. Based on dietary distinctions in different pig husbandry techniques, a management style was inferred based on the isotopic study. This suggests that the animals were free ranging in an extensive management system focused on larger herds of swine.

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Table of Contents

List of Tables

List of Figures

1 Introduction

Recent research in Classical archaeology has benefited from the inclusion of bioarchaeological methods such as stable isotope analysis, as these techniques can contribute to an increased understanding of domestic economy and daily life in antiquity (for example: Bourbou et al., 2013). Despite the success of this approach, few collaborative studies have utilized stable isotope methodology to explore daily life in Classical or Hellenistic Greece. My study supports ongoing analyses of domestic economy at the Hellenistic (323-31 BCE) site of Kastro Kallithea in Thessaly, Greece, through the stable isotope analysis of pig bones. This study is strongly related to one of the primary goals of the Kallithea project: gaining insight into the organization of the Hellenistic domestic economy. The immediate goal of my study is to determine the type(s) of pig husbandry implemented at the site by examining feeding patterns of pigs from the site.

An investigation of pig husbandry at Kastro Kallithea adds to our understanding of household economy in this Hellenistic community. This is a topic that has been studied through the lens of domestic architecture, settlement archaeology, and conventional faunal analysis (e.g. Haagsma, 2014; Surtees et al., 2014); as well as the stable isotope analysis of sheep and goat remains (Bishop et al., 2019). Pig husbandry has received increased attention in recent archaeological research, especially in the South Pacific (Shaw, et al., 2009). Despite the success of such studies in other parts of the world, few studies have analyzed ancient Greek pig husbandry practices. It has been suggested that pig husbandry is, in fact, understudied in ancient Greece with a reliance being placed on literary sources instead (MacKinnon, 2014a). Based on the indirect evidence available, including Late Bronze Age texts (Halstead & Isaakidou, 2011), studies from South West Turkey (Frémondeau, et al., 2017), and ethnographic studies in modern Greece (Albarella et al., 2011; Halstead & Isaakidou, 2011), I propose that two types of pig husbandry practices may have occurred in ancient Greece: (1) small scale management, wherein a few animals were raised in enclosures near the dwelling for use at the household level; and (2) larger, free-roaming extensively managed herds for economic gain. This pairing of management styles has been recorded in studies of ancient pig husbandry in Northern Europe (Hamilton & Thomas, 2012; Madgwick, Mulville, & Stevens, 2012) and China (Cucchi et al., 2016). One of the major challenges facing farmers is feeding their animals, and the type of choices that people make regarding their subsistence systems are markers of social importance (Balasse et al., 2016; Makarewicz, 2014; Redding, 2015). Cucchi et al. (2016) suggest that the Chinese pig management strategies emphasized in different eras may be linked to changes in social complexity. Understanding pig management, thus, provides key insights into economic complexity, daily life, and land use patterns in antiquity.

1.1 Animal Husbandry and the Economy

The management of animals is not simply an arbitrary set of cultural norms enacted by individuals in a population (Forbes, 1995). Instead, animal husbandry practices are the physical expression of rational social-economic choices made at an individual level as allowed by the environment, technology, and cultural considerations as well as the interactions between these factors. When considered this way, the value in examining ancient husbandry becomes apparent as it provides an opportunity to understand not only the diet of the animals but also provides insight into economic choices made by people in antiquity. This type of analysis circumvents issues of overgeneralization and breadth in the study of ancient economies, which has been criticized for being too static and general (Archibald, 2005). Although there has been concern about small site-specific studies of the ancient economy resulting in an *ad hoc* or piecemeal understanding of the economy (Archibald, 2005), as long as the data is contextualized within its site and relative to other sites, this should not be a problem.

1.2 Defining Animal Husbandry

To discuss pig husbandry, it is important to have a working definition of animal husbandry more generally. Animal husbandry can loosely be defined as the branch of agriculture focused on the use of domesticated animals for primary and secondary products. Husbandry includes feeding, day to day care, selective breeding, and slaughtering. The choices made are directly correlated to the purpose of the animals (such as meat, milk, wool, transport etc.) (Cherry, 1988), socioeconomic status, identity, or environmental constraints (Balasse et al., 2016; Cucchi et al., 2006; Makarewicz, 2014; Redding, 2015). These considerations conflict with each other regarding how the animals should be reared (i.e., animals cannot be raised for all the aforementioned purposes). Thus, there are different husbandry practices used depending on goals and constraints. These are often discussed in terms of scales of husbandry, the distinctions between which, as pointed out by Halstead and Isaakidou (2011), are arbitrary and generally fluid. Sophisticated husbandry practices do not have to take on the appearance of practices such as large scale pasturage or transhumance to be highly specialized (Cherry, 1988). Similarly, husbandry practices are relative to the size of the population: small scale rearing can appear differently based on social factors such as wealth, and ecological factors such as environmental conditions. Two predominant types of husbandry can be examined via stable isotope analysis: intensive husbandry and extensive husbandry.

1.2.1 Intensive Husbandry

Intensive animal husbandry focuses on high productivity of animals using small herds of animals which are foddered (Forbes, 1995). These relatively small-scale practices (the scale is relative) focus on a few animals, typically for fattening. Within this method, animals are either kept in controlled pastures or in pens, sometimes adjacent to households. Animals will be provided most of their food through foddering with grain, agricultural waste products, household waste, or human waste.

1.2.2 Extensive Husbandry

Extensive husbandry typically operates on a larger scale (in numbers of animals) than intensive husbandry (Forbes, 1995). With this method, animals are typically allowed to graze or scavenge in more open regions with little human input. Most of the animals' food is obtained via grazing or scavenging, with the potential for some supplementary foddering, making the animals primarily reliant on the landscape.

1.3 Pig Biology

The biology and behavior of pigs are important to understand as they impact the husbandry practices employed and, thus the stable isotopic signals of the pigs. Pigs, as omnivores, are opportunistic feeders (Hamilton et al., 2009). The plasticity of the domestic pig allows it to grow and reproduce in highly variable environments (Johnson & McGlone, 2011). Wild and domestic pigs can farrow once or twice a year (Frémondeau et al., 2017). This plasticity makes them malleable under human control and, thus, reflective of human economy (Halley & Rosvold, 2014).

1.4 Overview of Thesis

This thesis is divided into 11 chapters. Chapter 1 provides an overview of the research question as well as some background animal husbandry and pigs that are essential for the rest of this thesis.

Chapter 2 focuses on the region of Thessaly. It covers the topography, the people, and the history of Thessaly highlighting the complexity of the region. Overall, it provides a general introduction to understanding the landscape and background to the region.

Chapter 3 provides information on animals in ancient Greece. Animal sacrifice is highlighted as an important aspect of understanding animals in Greek antiquity due to the ubiquity of the practice. This is examined through multiple lines of evidence and provides a description of how animal sacrifice appears in the zooarchaeological record. This chapter also discusses the roles animals played in the economy.

Chapter 4 focuses on animal husbandry in ancient Greece. Numerous lines of evidence are used including bioarchaeological studies, written records, and modern analogy. This is contextualized in larger ongoing debates regarding agricultural practices in ancient Greece.

Chapter 5 provides an overview of the site of Kastro Kallithea. This includes a description of the layout of the site and an in depth look at Building 10. The faunal assemblage is also discussed in this chapter as a whole and Building 10 and Acropolis Building 1 separately. I also compare the faunal assemblage from Building 10 to that of New Halos as a comparative.

Chapter 6 provides a tailored overview of the theoretical background of stable isotope analysis. The foundation of carbon and nitrogen stable isotope systems are discussed including inter- and intra-individual variation at both the autotroph and heterotroph levels. This chapter also provides discussion of isotope routing in skeletal tissues.

Chapter 7 extends off the previous chapter to discuss applications of stable isotope analysis. This includes an overview of faunal isotopic studies in Greece as well as a review of the literature regarding interpretations of carbon and nitrogen stable isotopes and pig husbandry.

Chapter 8 focuses on the methods used in this study. An overview of the samples I used is provided, as well as a review of different methods for isolating collagen, and an in-depth description of the method I used. In addition, I have included an overview of diagenesis, how it impacts collagen, and the steps taken to avoid using compromised collagen.

Chapter 9 presents the data collected in this study. This includes the values for the collagen preservation indicators and the results of the carbon and nitrogen stable isotope analysis.

Chapter 10 contains the analysis and interpretation of the data collected. This is primarily focused on examining pig husbandry practices at Kastro Kallithea and understanding the variation that is seen. This chapter also compares the data from Kastro Kallithea to other sites in Greece with isotopic data for pigs.

Chapter 11 provides conclusions for this thesis including an overview of the study and possible directions of future research.

2 History and Topography

To understand pig husbandry practices utilized at Kastro Kallithea, it is important to understand the topography and history of the wider region of Thessaly. Throughout Antiquity, Thessaly was famously known for its wealth in natural resources, raising horses, cultivating grain, and for its military power (Graninger, 2010; Mili, 2015). Thessaly is less well studied than other regions of Greece, but there is still a significant amount of published scholarship. I will provide an overview of the topography and people of Thessaly, and then a brief overview of the history of the region.

2.1 Topography

Thessaly is an interesting region as it is markedly different socially and geographically than other districts of Greece (Morgan, 2003). It is bounded by natural geographical features with Mount Olympus to the north, the Pindus mountains to the west, the Othrys mountains to the south, the mountainous range of Pelion and Ossa to the southeast, and the Pagasetic Gulf to the east. The majority of Thessaly is comprised of four plains, two east and two west, separated by a mountain range. The western plains are more extensive; however, they are apt to flood, making the eastern plains better suited to agriculture. The corridor from the eastern plain towards the Pagasetic Gulf and the coastal plain of Almiros represents one of the few areas that facilitate a connection between land and sea; mountains separate most of Thessaly from the sea, creating an east/west delineation. Graninger (2010) notes the importance of topographic variation in Thessaly, drawing a distinction between the ‘outward-facing’ communities of the east with access to the sea and the ‘landward oriented’ communities of the west.

2.2 People of Thessaly

According to ancient myth, the Thessalians were relative latecomers to the region. Many groups, or *ethne*, have been thought to live in Thessaly including Pelasgians, Lapiths, Perrhabians, and Ainians (Mili, 2015). As reviewed by Mili (2015), there are a number of ancient theories regarding the genealogy of the Thessalians as well as how and when they arrived in Thessaly. Various authors describe different versions of events, but a common thread seems to be the expulsion of other populations connected to a lawful return by the children of Thessalos claiming land that was once theirs (Mili, 2015; van Wees, 2003). A popular story is the expulsion of the Boiotians from Thessaly, which is mentioned by Thucydides (Thuc. 1.12.3) and by Archemachos, who states that those who did not go back to Boiotia stayed behind as *penestai* (Ath. 6.85). Strabo's description of a Boiotian cult moving from Arne (in Thessaly) to Koroneia has been used as evidence to support this theory (Strab 9.2.30; Graninger, 2011; Mili, 2015). The old inhabitants of Thessaly are thought to have become *perioikoi*, *penestai*, or neighboring *ethne*, or to have migrated out of the region completely (Mili, 2015). Although it remains unclear who the 'original people' (if such a thing existed) of Thessaly were, the existence of these arguments shows that the ancient Greeks had long memories, even if invented, of the history of the region.

The term *perioikoi* means 'surrounding households' and refers to people that 'lived around' the main Thessalian plains including the Perrhaibians to the north, the Magnesians to the east, the Dolopians to the southwest, and the Phthiotic Achaians to the south and southeast (Graninger, 2011). Thessalians controlled the *perioikoi* starting in the 6th c. BCE until the invasion of Phillip II (Graninger, 2010). The relationship between the *perioikoi* and the Thessalian ethnos is not fully understood, but it appears that the *perioikic ethne* were equal to

Thessalians, though they were perhaps politically subservient or under some form of hegemonic alliance (Graninger, 2011). The *perioikoi* were politically independent, having independent votes in the Amphyctyonic council in Delphi, and well connected enough to join together in taking administrative roles (Graninger, 2011).

Conversely, the *penestai* (Ducat, 1994) were an agricultural serf-like class whose role bore resemblances (according to both modern and ancient scholars) to that of the helots of Sparta (Graninger, 2011; van Wees, 2003). A lack of early information regarding the *penestai* makes understanding their origins and history difficult (Morgan, 2003). Their claimed origins include Thessalian, Perrhaibian, Magnesian, and Boiotian (Graninger, 2011). Whether the *penestai* were actually a conquered people is debated; it is alternatively suggested that they became subordinated by constitutional means (Graninger, 2011). The *penestai* were rural laborers who were privately owned in large numbers, forming much of the agrarian workforce within Thessaly (Graninger, 2011; Mili, 2015; van Wees, 2003). They were liable to military service and had limited rights which consisted of protection from being put to death and against being moved out of the country (van Wees, 2003). Descriptions of the status of *penestai* suggest dependency on their masters for food and, perhaps, money (van Wees, 2003). Although it is unclear exactly what the status of the *penestai* was, many scholars agree with the *Onomastikon* by Pollux that states that the *penestai's* position was between free and slave (Poll. *Onom*. 3.83).

2.3 History of Thessaly

The following section is a brief overview of the prehistory and history of Thessaly to the Roman period. I focus predominately on socio-political changes that occurred during these time periods with an emphasis on the trade and subsistence economy. The evidence for life in these periods comes from a mix of archaeological and literary sources, with the literary sources becoming more dominant in later periods.

2.3.1 Before the Neolithic

The earliest human presence in Greece dates to 300,000 - 400,000 years ago, but there are limited identifiable sites until approximately 150,000 BP (Thomas, 2014). Evidence of human occupation in the late Paleolithic suggests that people hunted animals and gathered wild plants, with increased variation in species used over time (Thomas, 2014). Few sites from the Mesolithic (9500-8000BP) have been identified; it is debated whether the scarcity of sites reflects insufficient research or poor preservation (Perlès, 2001). Material remains from these sites suggest that their populations were likely mobile rather than sedentary (Perlès, 2001). The emergence of settled (at least semi-permanent) farming villages marks the start of the Neolithic (Thomas, 2014).

2.3.2 The Neolithic Period

Interestingly, Thessaly is the focal point for research on the Greek Neolithic with the coastal region being the most intensively excavated (Andreou et al., 1996). As reviewed by Perlès (1999), the distribution of Neolithic sites in Thessaly appears to be uneven and clustered. It has been suggested that the increase in sites from the Mesolithic may be due to a demic diffusion, but rapid growth may have also been facilitated by socio-economic and environmental factors (Perlès, 2001). Throughout the Neolithic an increasingly complex economy developed (Thomas, 2014).

The Early Neolithic saw the expansion of farming into the region, accompanied by an increasing number of large villages (Perlès, 2001). The village, likely comprised of a single extended family, would make up the primary community for most individuals (Thomas, 2014). A non-indigenous model of domestication is widely accepted, based on timing of appearance and evidence for a single (non-indigenous) origin for both domesticated plants and animals (Perlés, 2001). The subsistence economy revolved around farming combined with animal husbandry (sheep, goat, cow, and pig) (Thomas, 2014), but the roles that each of these played in the diet and economy are debated (Perlés, 2001). Perlés (2001) suggests that herds of sheep and goat were likely more of a social necessity rather than the cornerstone of the subsistence economy, seeing as the number of domesticates would have initially been too low for animal products to have played a large role in the diet.

2.3.3 Mycenaean Thessaly

Much of the research interest in Bronze Age Thessaly derives from its position at the northern edge of the Mycenaean world (Feuer, 1975). The Mycenaean world is typically understood through a center and periphery model in which major sites on the Peloponnese, like Mycenae and Tiryns, are the 'centers' of Mycenaean culture, while regions farther away are 'peripheral' (Papadimitriou, 2008). Papadimitriou (2008) suggests two major issues with this model: 1) it portrays Mycenaean culture as static, and 2) it attributes development of Thessaly during this time period as a result of exogenous factors over which the inhabitants of the region had no agency. The center and periphery model also defines a singular "ideal" Mycenaean culture to which everything else is compared rather than attempting to understand Mycenaeanization as a process of interactions between populations.

To understand Thessaly's position in the Mycenaean world, it is useful to describe the basis of what it meant to be "Mycenaean". Mycenaean culture, as described by Papadimitriou (2008), is the material expression of a specific mode of social, political, and economic organization. There are a number of markers of this material expression including linear B inscriptions, Mycenaean pottery, tholos tombs, and palatial structures. The cornerstone of Mycenaean culture, the palace, was not just the physical structure of the Megaron or the seat of the *wanax*, but a symbolic concept with economic, administrative, military, political, and religious functions (Arena, 2015; Papadimitriou, 2008). These functions included the production of luxury goods, storage (and potentially redistribution) of agricultural projects, external trade, and cult activity with specific symbols (Papadimitriou, 2008). The palatial unit comprised a highly complex system of organization with the ability to mobilize goods and labor (Arena, 2015). Thus, Mycenaeanization refers to a region's integration into and response to the specific socio-economic and administrative styles of Mycenaean culture resulting in a broad variety of responses (Papadimitriou, 2008).

Mycenaean culture in Thessaly has been identified by the presence of linear B inscriptions, Mycenaean pottery (replicas and originals), tholos tombs, and palaces (Mili, 2015; Papadimitriou, 2008). Importantly, Mycenaean style ceramics were not only imported from elsewhere but appear to have been made locally in Thessaly, based on chemical determination of clay sources (Feuer & Schneider, 2003). Papadimitriou (2008) proposed three conditions for the development of Mycenaean palaces: close proximity to alluvial plains, direct association with ports, and steady access to metal resources, especially copper and tin. The coastal area around Volos fits two of these conditions (alluvial plains and ports); it is unclear whether metal was readily available. Candidate sites that may have palatial structures include Dimini (Adrymi-Sismani, 2007), Volos, and Pefkakia (Papadimitriou, 2008). Of these, it appears that if a true Mycenaean palace did exist in Thessaly, it was likely at Dimini where two large tholos tombs have been excavated, as well as a large megaron-type building that appears to have fulfilled the majority of the functions of a palace. The lack of identifiably Mycenaean sites in Western Thessaly has been suggested to stem from climactic and geographical factors in the Early Bronze Age that favored economic division and intensification in the coastal regions (Feuer, 1983).

Mycenaean culture may have only been partially established in Thessaly. Papadimitriou (2008) and Boyd (2016) suggest that what has been recognized as “complete Mycenaeanization” may actually reflect elite uniformity rather than cultural homogeneity, and that Mycenaean culture did not penetrate deeply into areas further inland where conditions were less favorable. Tholos tombs, while certainly present, seem to have been adopted by restricted social groups who did not create large cemeteries (Boyd, 2016). Arena (2015) mirrors this claim and suggests that the presence of tholos tombs throughout Thessaly was not reproduction of Mycenaean culture but rather representative of a claim to status. This is supported by Feuer (1975) who noted that built tombs and cist tombs are common, as are burial sites where Mycenaean and non-Mycenaean traditions co-exist, suggesting continuity of non-Mycenaean practices.

Without the solid evidence of an economy organized according to a Mycenaean model (identified by palatial structures and a homogenous Mycenean presence), it is difficult to say anything definitive on economic interactions in Mycenaean Thessaly. Based on a synthesis of the archaeological evidence available, Thomas (2014) suggests that economic diversification, increase in settlements and social stratification, and widespread trade occurred throughout this period. This likely included bronze technology as well as olive and grape cultivation (Thomas, 2014).

2.3.4 Iron Age

The end of the Bronze Age represents the beginning of the period traditionally denoted in the Mediterranean world as the Dark Ages. Characteristic of this period are institutional change and population decline (Thomas, 2014). Interestingly, this seemed to affect Thessaly less severely than other regions — although Thessaly certainly did not escape the major cultural changes that accompany the end of the Bronze Age in Greece (Feuer, 1983). While 'Megaron B' in the Mycenaean town near Dimini underwent major destruction like many other Mycenaean centers in the Aegean world, cultural continuity is noted throughout the period (Georganas, 2011; Thomas, 2014). Mycenaean burial customs persisted into the Iron Age, possibly due to Thessaly's isolation (Georganas, 2011). Continuity can be seen in cemetery structures; for example, the cemetery of Nea Ionia at Volos shows continuous use from the Late Bronze Age through to the Early Iron Age (Georganas, 2011).

As reviewed by Morgan (2009), Iron Age population decline has been suggested based on a distinct decrease in the number of sites; however, this may be an artifact of excavation strategy. As a result, much human activity is invisible in the archaeological record, with the exception of graves, so it is hard to tell if there is a decrease in the number of sites. As with most periods, rescue excavations have dominated Iron Age sites in Thessaly; distribution maps of Early Iron Age (EIA) evidence cannot, therefore, be seen as an accurate representation of the sites present (Morgan, 2003). Overall, the depopulation in Thessaly was likely less dramatic and less directly tied to events accompanying the end of the LBA that initially thought (Morgan, 2009). Morgan (2009) suggests population changes may actually be long term cycles of settlement movement including the creation and abandonment of sites in and around the Pagasetic gulf.

Regarding the economy in the Iron Age, there is development of local markets as well as an increased importance of sanctuaries as centers of manufacturing (Morgan, 2009). This intertwining of sacred and secular activities becomes more complex through the Iron Age with the expansion of cult systems and activity. This provides an interesting problem in the study of ancient Greek economy as economic activity becomes deeply embedded in religion and vice versa, creating a system where the sacred cannot easily be (and arguably should not be) separated from the secular. The increase in cult activity correlates with changes in animal sacrifice, using components from Mycenaean sacrifice and feasting, but also taking its own form at this point (Morgan, 2009). There is no wholesale shift to pastoralism in Thessaly during the EIA (Morgan, 2009), but like elsewhere in Greece, domesticated animals must have represented considerable wealth for Thessaly's inhabitants.

2.3.5 Archaic and Classical Periods

During the Archaic and Classical periods, there is an increase in the number of available historical sources. Although these add depth to the archaeological record (which is, like that of the Iron Age, primarily based on salvage excavations with little published), they tend to be Athenocentric and, thus, not directly applicable to Thessaly.

Thessaly, during the Classical and Archaic periods, was similar to the rest of Greece — a region where *poleis* developed, albeit later than other regions of the Aegean (Graninger, 2010). Yet, Thessaly is a region where another form of political organization developed too: the *ethnos*. An expansion and replication of cities in this period can be linked to population growth in the seventh and eighth centuries (Thomas, 2014).

Much of the information about state formation in Thessaly is mytho-historical, dating back to pre-Iron Age times. Early accounts of Thessaly-wide law are attributed to the quasi-mythological

Aleuas the Red of Larissa who divided Thessaly into four tetrads (or *moirai*) — Hestiaiotis (NW), Pelasgiotis (NE), Phthiotis (SE) and Thessaliotis (SW) — in the 6th century (Morgan, 2003). The tetrads appear to have served an administrative role within Thessaly and were further divided into *kleroi* for military recruitment quota purposes (Arist. fr. 498 Rose; Graninger, 2011).

By the 4th century, inscriptions and historical sources suggest that a singular over-arching League, called the *koinon,* controlled Thessaly (Graninger, 2011). By the end of the Classical period, the system of a single leader of Thessaly was securely established as demonstrated by the presence of Jason of Pherai (Sprawski, 1999).

At the end of the Archaic period, Thessaly sided with the Persians in the Persian War under the influence of the Aleuads. After this, Thessaly ceased to be a major player in Panhellenic affairs (though it was still active in the management of Panhellenic sanctuaries).

During the Third Sacred War (356-346 BCE), Thessaly fell under Macedonian control after calling on Phillip II, King of Macedonia, for assistance fighting the Pheraians. Phillip II was named the *archon* of the Thessalian League, a title which, upon his death, was transferred to his son, Alexander the Great.

By the Archaic period, each of Thessaly's tetrads contained cities dominated by leading families (Morgan, 2003). These families drew power from large agrarian estates worked by *penestai* (Graninger, 2010). Politically, there was a balance of power between competing families creating complex internal affairs including wars within and between cities (Graninger, 2010).

There is debate about the complexity of the economy in the Archaic and later periods. Primitivists maintain that the foundation of the Greek economy in the first millennium BCE was aimed at subsistence and self-sufficiency, with little to no focus on exchange (van Wees, 2009). Conversely, modernists believe that the market played an important role in the economy and that people relied heavily on trade (van Wees, 2009). This debate will be discussed more fully in Chapter 3. Although the people of Archaic Thessaly and later periods are often imagined as subsistence farmers ruled by a small elite, van Wees (2009) argues that the economy would have been far more complex.

2.3.6 Hellenistic and Roman Periods

The Hellenistic period is especially important for this thesis as this is the period in which Kastro Kallithea flourished. Compared to the Classical period, there are far fewer complete literary sources shaping our understanding of the history of the Hellenistic. This is particularly true for Thessaly as the preserved sources are, again, primarily Athenocentric. Many of the authors writing about this period, such as Diodorus Siculus, lived at the end of the Hellenistic period. As reviewed by Erskine (2005), the Classical period has a number of dominating texts that shape how we think about the period, the interpretive framework used, and, subsequently, our investigations of the past. The literary sources that have survived from the Hellenistic period are largely fragmentary, known only from later writers' citations, and scattered widely in time and space (Erskine, 2005; Wiemer, 2013). As highlighted by Meeus (2013), this gap in the evidence does not suggest that the period was unimportant; it simply reflects the fact that few sources of the era survived. There is, however, other rich evidence for the period, specifically with regards to Thessaly, as there are many fortification walls and towers visible throughout the region; the challenge is pulling the various strands of evidence together to create a full picture of the era (Erskine, 2005). This lack of literary evidence changes with the presence of the Romans in the east, which begins an era of richer evidence (albeit mainly regarding matters important to Romans) (Erskine, 2005).

The central feature of the Hellenistic period is the establishment of the Greek monarchies by Alexander the Great (Price, 1991). Alexander the Great succeeded to the throne of Macedon upon the death of his father, Phillip II. He led a series of campaigns to punish the Persians through which he gained control of the Persian empire, which he then expanded. His unexpected death led to struggles between a number of the empire's powerful individuals, each of whom wanted to be Alexander's sole successor. From these conflicts, four main Hellenistic kingdoms emerged: the Ptolemaic Kingdom, the Antigonid Kingdom, the Attalid Kingdom, and the Seleucid Kingdom (Price, 1991). The conflict changed the Hellenistic world from a stable empire to a plurality of kingdoms that were intensely competitive and unstable (Wiemer, 2013).

Macedonian rule in Thessaly started at the end of the 4th century BCE when Thessaly became a battlefield as Polyperchon moved into Thessaly to gain control, struggling with Cassander and the Antigonids. Demetrios Poliorketes eventually achieved victory for the Macedonians in c. 302 BCE when he 'liberated' part of Thessaly (Diod. 18.38.6). Some key features of this period (the late 4th – early 3rd c. BCE) in Thessaly were changes in settlement patterns, the construction of numerous fortification walls, and the creation of new urban centres (Chykerda, 2010; Surtees, Karapanou, & Haagsma, 2014). An example of this change in settlement patterns was the creation of the new important port city of Demetrias, giving the Macedonians a foothold in Greece on an important trade route. The formation of Demetrias was achieved through a *synoikismos* of smaller towns including Neleia, Pagasai, Ormenion, Rhizous, Sepias, Olizon, Boibe, and Iolkos (Batziou-Efstathiou, 2002; Batziou-Efstathiou, 1996). A discussion of the economy of Hellenistic Thessaly can be found in Chapter 3.

The period of rule by the Macedonians was relatively stable until Titus Quinctius Flamininus, leader of the Roman army, came to Greece with the defeat of the Macedonians at Kynoskephalai in 197 BCE. In 196 BCE, Flamininus instituted territorial reforms throughout Greece; creating the Thessalian League, which was the first historical reference to a formal *koinon* (Graninger, 2011). The Thessalian League eventually involved all the tetrads and *perioikoi* with the exception of Magnesia, which did not become incorporated until the reign of Diocletian (Graninger, 2006).

Augustus reorganized the Roman provinces in 27 BCE and placed Thessaly into the province of Achaia (Graninger, 2006). During this period, Thessaly lost ten of its twelve votes in the Delphic Amphictyony, as the various *ethne* of Thessaly were now considered "Thessalian", and were unified as a single identity (Graninger, 2011).

2.4 Chapter Summary

As this chapter demonstrates, Thessaly has a very long and complex history. Evidence from the archaeological and literary sources shows how socio-political changes occurred from before the Neolithic through to the Roman period. The Neolithic period saw the expansion of farming among many large villages and the Mycenaean period revolved around palaces (even if Mycenaean culture was only partially established in Thessaly). The Iron Age saw the development of local markets as well as religious sanctuaries as centres of manufacturing. The Archaic and Classical periods brought about the traditional state formation of Thessaly into tetrads and *perioikoi* as well as possibly the first informal Thessalian league. Constant power struggles were the key factor in the in the Hellenistic period, which resulted in changes in settlement patterns, numerous fortification walls, and new urban centres being formed. The

Romans eventually gained control of Thessaly after the battle of Kynoskephalai in 197 BCE, instituted territorial reforms and created the first formal Thessalian league. In 27 BCE, Augustus reorganized the Roman provinces and unified the region of Thessaly as a group of peoples with a single identity.

3 Animals in Ancient Greece

This chapter will provide an introduction to animals in ancient Greece. In the first part of this chapter, I will discuss animal sacrifice as this is one of the more visible aspects of animal life (and death) in ancient Greece. Along with being pervasive in ancient and modern thought, animal sacrifice also informs the zooarchaeological assemblages, making it an essential topic for understanding the context of the animal samples used in this study. I will then move on to discuss the hunting of animals and meat eating in the ancient world. Finally, the third portion of this chapter will examine the role of animals in the ancient economy.

3.1 Animal Sacrifice

Animal sacrifice in ancient Greece has been an important topic of study since the 1970s, and is often considered the most important aspect of ritual (Burkert, 1983; Detienne & Vernant, 1989; Ekroth, 2014b; Faraone & Naiden, 2012; Girard, 1972). Given this importance, there has been an increasing research interest in ancient sacrifice, resulting in numerous studies using a number of approaches. Initial studies examined the literary texts, inscriptions, and images; archaeological evidence, such as faunal remains, was incorporated later (Ekroth, 2014b). Due to the relatively late introduction of zooarchaeology to this literature, there has been significantly less zooarchaeological work examining animal sacrifice and its importance in ancient Greek cults compared to other forms of analysis, such as literary evidence.

3.1.1 Discourse on Sacrifice

The history of academic thought regarding ritualistic animal sacrifice in ancient Greece is critical to an understanding of its position in the literature. The study of animal sacrifice in ancient Greece gained importance in the 1970s with a series of publications, including Burkert (1983) *Homo Necans*, Girard (1972) *Violence and the Sacred*, and Detienne and Vernant (1989) *The Cuisine of Sacrifice Among the Gods*. The primary interest of these authors was to create "grand philosophical theorizations" (Graf, 2012) that could increase scholars' understanding of ritual sacrifice in ancient Greece. Burkert views the act of killing as the essential feature of animal sacrifice and religion more broadly relating this to Neolithic hunting (Burkert, 1983; Graf, 2012). Girard also approaches animal sacrifice through the lens of killing suggesting that ritualistic killing, as part of religious practices, acts as a control on man's primal desire to kill (Girard, 1972; Graf, 2012). Conversely, Vernant focuses on the physical aspects of cooking and consuming sacrificed animals in relation to social implications regarding how meat is distributed (Detienne & Vernant, 1989; Faraone & Naiden, 2012b). Although they differ in their specific theories on animal sacrifice, they all treat religion to be a "tradition of cultural action" (Faraone & Naiden, 2012b), rather than a set of beliefs, and treat sacrifice as the most important ritual in Greek cult activity (Faraone & Naiden, 2012a). As Faraone and Naiden (2012) point out, however, this status has never been self-evident. A common critique of these approaches to animal sacrifice is the monolithic, static nature assumed for sacrifice, that is, studying it as a universal institution rather than in its varying contexts (Stavrianopoulou, 2008). Rives (2011) suggests that cult rituals varied widely in their goals and methods, and thus cannot be considered a single category.

Recent studies on animal sacrifice emphasize the need for a fluid interpretive scope for understanding ritualistic sacrifice and, thus, are reliant on cultural context (Stavrianopoulou, 2008). Scholars such as deFrance (2009) focus on the social meaning and manipulation of the animals being sacrificed, and the ceremonial aspect of animal sacrifice. Ekroth (2019) suggests that Greek animal sacrifice is not a single ritual, but a set of rituals too diverse to be understood through one lens. Recent work, as reviewed by MacKinnon (2018), has moved away from the sacred versus secular dichotomy in ancient Greek religion and sacrifice, and towards understanding sacrifice as part of a larger, multidimensional picture of cult activity. These approaches are beneficial as they treat ancient sacrifice not only as a product of culture, but as an intrinsic part of economy, political, and daily life, and provide a more fluid view of sacrifice. This allows sacrifice to be considered as a dynamic part of culture rather that a static category.

3.1.2 Sacrificing Animals

Regardless of the framework used to conceptualize cult animal sacrifice, some basic aspects of ancient Greek ritual sacrifice can be defined: i) there had to be a recipient for the sacrifice, and it must be offered to or directed at them – this linked man to god (McClymond, 2008), ii) animals were whole and unblemished, with certain gods sometimes having specific preferences as to the type of animals sacrificed to them (Pedley, 2005), and iii) numerous types of sacrifice existed which, according to Theophrastos, were classified based on the motivation of the sacrifice (*De Abstinentia* II, 24 (Budé) = W. Pötscher, *Theophrastos Περὶ Εὐσεβείας* (1964), fr. 12, lines 42-44; Lindenlauf, 2000). Although there is fairly strong evidence for these basic aspects, it is important to note that there was variation in tradition based on cult, region, deity, and context. Specific forms of sacrifice are important to understanding processes leading to faunal assemblage formation, including processing and deposition of remains.

The most common sacrifice is thought to be the *thysia*, which was likely preceded by a festival procession, initiation rituals, vegetal offerings, and prayers followed by the burning of symbolic parts of the animals, libation, and consumption (Ekroth, 2017a, 2019; Hitch, Naiden, &

Rutherford, 2017). In a *thysia* sacrifice, the animal was divided between the gods and men — the gods received specific portions burnt on the altar and the worshippers consumed a portion of the meat (Ekroth, 2007, 2017a). The smoke rising up to the gods from the altar was thought to be thick, fatty, and enjoyable (Ekroth, 2005). The portions offered to the gods appears to have varied, but were typically the parts inedible (or avoided) by humans (Lindenlauf, 2000); this variation is summarized in Table 3.1. The portion intended for the humans was divided by weight amongst all of the worshippers and was consumed in the sanctuary, taken home to eat, or sold (Ekroth, 2019). In other rituals, holocaust sacrifices were performed; the entire animal was burnt in the fire with no meat available for mortal consumption (Ekroth, 2017a). These were likely less frequent and used small cheap animal victims such as piglets, kids, or lambs (Ekroth, 2019). Although the *thysia* and holocaust sacrifices likely served different purposes, they were similar in that burning allowed the sacrifice, through the smoke, to travel to the gods above. This type of sacrifice, however, does not make sense for chthonic deities (those that lived in the ground). For chthonic deities, sacrifices such as libations or bloodletting were more likely (Ekroth, 2017a). *Sphagia* sacrifices, like holocaust sacrifices, did not include meat consumption after the sacrifice; this type of sacrifice would have occurred at a battlefield and involved the killing and bleeding of an animal (typically a ram) (Ekroth, 2019).

Although animal sacrifice is often treated as the most important aspect of the rituals, they could also include vegetal offerings; these were common in funerary rituals, but also occurred in cults sometimes as a complement to the *thysia* (Ekroth, 2002).

Table 3.1: Parts of the sacrificed animal given to the gods according to ancient sources. Adapted from Lindenlauf (2000).

Author	*Thigh Bone*	*Fat*	*Loin*	*Tail*	*Gallbladder*	*Various*
Hom. Il. *1. 460-3; Od. 3. 456-9; 14. 427-9*	X	X				Raw meat from all over the body
Hom. Od. *3.341*						Tongue
Hes, Th. *540-1*		X				White bones
A. *Pr. 496-9*	X	X	X			
S. Ant. *1005-11*	X	X			X	
Ar. Pax. *1053-5*	X		X	X		
Ar. Th. *693*	X					
Ar. Ach.*784-5*				X		
Ar. Av. *290-3,1230-3*	X	X				
Phercer. fr. *28 (Kassel-Austin)*	X		X	X		
Eub. fr.*127 (Kassel-Austin)*	X			X		
Eub. fr. *94 (Kassel-Austin)*		X				
Men. Dys. *447-53*			X		X	
SEG 35 (1985) 113; 36 (1986) 206; (3rd c. B.C.)	X					Meat from the shoulders

3.1.3 Iconographic and Literary Evidence for Animal Sacrifice

The iconographic and textual support for understanding animal sacrifice, when present, is often inconclusive. Although descriptions and depictions of sacrifice exist, the ancient Greeks often portrayed an ideal version of sacrifice, rather than actual sacrifice details (van Straten, 1995). The literature also does not provide a uniform portrayal of the sacrifice, as the sacrifice itself is often not depicted. Iconography suggests that the gods' portion at the *thysia* sacrifice contained the tail, whereas the literary evidence suggests the burning of the thighbone (Ekroth, 2017a). Other forms of sacrifice do not appear readily in either iconography or literature. Images are not helpful in understanding the sacrifice as they are often composed of stock motifs

(Klöckner (2017) and, as noted by Ekroth (2017) are more representative of choices of how to represent Greek sacrifice rather than how they actually occurred.

3.1.4 Zooarchaeological Evidence for Animal Sacrifice

Although reporting biological, ecological, and cultural data from faunal assemblages at ancient Greek sites is becoming more common, the systematic study of sanctuaries through the examination of faunal assemblages is almost non-existent (Bookidis et al., 1999; MacKinnon, 2007, 2018).

Zooarchaeological evidence of sacrifice typically uses faunal remains within the *temenos* of the sanctuary. The tangible results of animal sacrifice are twofold in *thysia* sacrifices: 1) the burnt portions for the gods result in heavily burnt and calcined bones; 2) the portions for humans would typically be grilled or boiled, producing less heavily altered bone refuse (Ekroth, 2017b). Dining debris from meat consumed at the sanctuary would typically be deposited with votives (Ekroth, 2017b).

Although the incorporation of zooarchaeological methods into the study of Greek religion and classical archaeology has increased recently, it is still relatively uncommon. Early uses of faunal analysis emphasized the practice of calculating meat weight (Naiden, 2012), a problematic methodology reviewed in Lyman (2008). This is changing as researchers are transitioning to more nuanced applications of faunal analysis, yet few zooarchaeological studies have attempted to discuss Greek sacrificial ritual in a comprehensive manner (Ekroth, 2017a). A number of studies have emphasized the importance and utility of faunal remains, specifically in studies of Greek cult practice, arguing for a more prominent role of zooarchaeology within classical archaeology.

Animal sacrifice following the traditional patterns described above has very limited archaeological visibility as there are not always concrete indicators on the remains and thus sacrifice can only be identified by context (i.e. physically being deposited in a sanctuary) (Hamilakis & Konsolaki, 2004). There is, however, an abundance of faunal skeletal remains that can be studied, and the amount of material will only continue to increase with increasing interest and excavation methods aimed at retaining faunal bones, making this a rich source of evidence (Ekroth, 2017a; Scullion, 2013; Wallensten & Ekroth, 2013). Interpretation of cultic activity requires incorporating multiple lines of evidence, and faunal analysis adds another layer of information (MacKinnon, 2018). Faunal analysis has the potential to reveal issues in aspects of cult that are *thought* to be already understood, and add facets of information not found in other sources (Ekroth, 2017a; Wallensten & Ekroth, 2013).

Faunal remains are the most direct evidence available for examining animal sacrifice (Ekroth, 2017a; Wallensten & Ekroth, 2013). Through its selection, butchery, treatment, and consumption, the animal represents not only communication with the gods but also the choices, habits, and behaviors of the *people* involved in the cultic activity (MacKinnon, 2018; Wallensten & Ekroth, 2013).

Faunal analysis examines three primary aspects of animal sacrifice: activity at the altar, consumption, and butchering refuse (Ekroth, 2017a). To distinguish these three categories, a large amount of contextual data must be examined, as the find location of the faunal remains does not dictate their use but rather their disposal. The primary means of distinguishing the categories is the condition of the bone as ancient sources specified that sacrificial burning and cooking were different practices (Lindenlauf, 2000). Activity at the altar will produce burned animal bone that will likely be carbonized or calcined, and will likely primarily include thighbones and tails (offerings to the gods) (Ekroth, 2017a; Nicholson, 1993). Consumption debris will have a lower quantity of burned bone as the meat was typically boiled or stewed (Ekroth, 2014b, 2017a; Lindenlauf, 2000). Boiled bone is difficult to recognize in archaeological settings as the minimal changes bone undergoes in boiling mimic diagenetic effects of the depositional environment (Roberts et al., 2002). If the meat was grilled, burning might be present but it would be to a lesser degree, occurring on the periphery of the bone not covered by meat (Ekroth, 2017a), and likely manifesting as charring (Nicholson, 1993). Cut and chop marks would also be expected. The bones present will likely correspond to parts of the animal high in meat. Finally, butchering refuse is expected to be unburned, likely containing elements with little meat.

3.1.5 Pig Sacrifice

Ekroth (2017) suggests that the low proportion of pig bones typically present in faunal assemblages is surprising, perhaps indicating that pigs were not always sacrificed in the *thysia* manner, which could influence their taphonomic and life histories. The majority of pigs sacrificed were young animals, likely as minor offerings as a part of more complex rituals (Jameson, 2014). Pigs are known to have been used for purifying rituals that relied primarily on blood-letting, rather than sacrificial burning (Ekroth, 2002). Purification rituals would have occurred before meetings of the assembly and council in Athens, regularly at some sanctuaries, and for some armies (van Straten, 1995). The fauna used in purification rituals, however, appear to not have been consumed (Lindenlauf, 2000).

Pig sacrifice is often linked to the goddess Demeter (a chthonic deity) (Scholiast on Lucian, *Dial. Meretr*. 2.1; Bremmer, 2007). The goddess Demeter was worshipped throughout ancient Greece (Cole, 1994). Unlike many other gods, where variation in worship appears to be normal, there appears to have been a general uniformity in her worship based on the regularity of votive offerings (Cole, 1994). This is likely due to her association with agriculture, giving her worship “clearly defined functions” (Cole, 1994). Her agricultural function can be seen in the votive offerings which typically are simple and modest and include miniature water- or grain-carrying vessels, as well as figurines carrying *hydriae*, plants, and animals. Another idea involves agricultural practice: Demeter is linked with ideas of agriculture and, pigs, if foddered, could be representative of agriculture. In Thessaly, cults of Demeter and Dionysus are often linked, and appear to have been popular (Mili, 2015). Many of the votive offerings found at Demeter sanctuaries in Thessaly are horse figurines, likely linked to the importance of horses in Thessaly, the myth of Demeter mating with Poseidon in the form of a horse, or other symbolism we are not aware of (Mili, 2015).

Ekroth (2019) notes a discrepancy between the faunal bone assemblages found at altars, and those associated with meal debris – typically altar assemblages contain cattle, sheep, and goat remains whereas meal debris contains the three aforementioned species as well as pig, horse, game, and dog. This might suggest that pigs were consumed as part of ritualized feasting but were not part of the main sacrifice. Alternatively, this inconsistency may be the result of different types of sacrifice occurring, or the remains of pigs being treated differently than other animals.

3.2 Hunting Animals

Although there is a plethora of primary sources and evidence regarding hunting, it is difficult to ascertain reliable accounts of hunting (MacKinnon, 2014b). Deer and boar hunting receive a lot of attention in ancient sources (see Eur. *Her.* 375-379; Apollod. *Epit.* E.3.22-23; Apollod. 1.8; Aristoph. *Wasps.* 1200-1204), but hare hunting would likely have been a more common practice. Boar hunting is notable for the danger involved, so was often performed to assert heroism or courage, or as an initiation (MacKinnon, 2014b). As only domesticated animals were used in sacrificial offerings, hunted animals would not have been sacrificed (MacKinnon, 2018).

Table 3.2 Prices of sacrificial victims in Drachmae. Adapted from Jameson (2014).

	Marathon	*Erchia*	*Athens* *(State Calendar)*
Ox or Cow	90	-	-
Calf (juvenile cow)	-	-	25
Pregnant Pig	20	-	-
Ram (male sheep)	12	10(?)	17
Pregnant Ewe (female goat)	16	10	-
Wether (castrated male sheep)	12	12	15
Ewe (female Sheep)	12	10	12
Male Goat	11	12	-
Doe (female goat)	-	10	-
Lamb (juvenile sheep)	-	7	4
Kid (juvenile goat)	-	5	-
Suckling Pig	3	3	3

3.2.1 Sacrifice and Meat Eating

There is no consensus regarding meat eating in ancient Greece; the varying views differ on what is considered sacred while regional differences in ritual practices are rarely considered. A well-known etiological myth regarding sacrifice to the gods comes from Hesiod's *Theogony* in the Prometheus myth. In this myth, the practice of sacrifice is explained by setting the origin of the practice in a mythical setting, separate from space and time: Prometheus plays a trick on Zeus by placing two meals in front of him, one of bones covered in fat (made to look delicious) and one of animal meat in an ox's stomach. Zeus knowingly chose the meal of bones and fat and, as a result, humans primarily sacrificed bones and fat to the gods thereafter (Hes. *Th.* 535-565).

During a typical *thysia* sacrifice at a sanctuary, people in attendance would have likely eaten a share of the meat. Meat was likely not a large part of the diet and most of what was consumed was likely from sacrifice (Ekroth, 2014a). It is unclear if meat was allowed to be removed from the sanctuary; Lindenlauf (2000) suggests that this was not always the case, whereas Acton (2014) suggests that prime cuts of meat would have been used for sacrifice and that other types of meat products such as sausage, mince, and blood sausages would have been readily available for sale outside the *temenos*. Ekroth (2014a; 2017b) suggests that meals resulting from animal sacrifice could have occurred anywhere within the sanctuary or at home – with some sanctuaries being more obvious as they had kitchens and dining areas. Osborne (1983) argues that animals could be killed without religious overtones; Jameson (1988) and Detienne (1989), however, suggest that Greeks would have only eaten meat that was directly or indirectly linked to animal sacrifice. This is further complicated by household sacrifice in which individual families and their guests could partake in a sacrifice, likely resulting in meat being available (van Straten, 1915). Additionally, hunting would have also contributed to the meat consumed (MacKinnon, 2014b).

3.3 Animals in the Economy

It is not uncommon for ancient economies to be viewed as agrarian and, therefore, simple and primitive (Murray, 1991). This view, however, ignores the choices made by people and the cultural factors that formed the economy. To understand the role of animals in the ancient economy, it is essential to discuss models of Hellenistic Thessaly's economy. The ancient economy is difficult to summarize as Hellenistic Thessaly encapsulates a myriad of political units (Cartledge et al., 2002). Historically, discussions have focused on two ongoing debates, the earlier of these being between primitivists and modernists. Primitivists suggest that it is inappropriate to assume that the ancient economy would have functioned similarly to the modern one; instead they suggest that the economy was primarily agriculture-based with a focus on self-sufficiency (Chandezon, 2011). Conversely, modernists argue that the ancient economy functioned similarly to a modern economy and was, therefore, more complex than believed by primitivists. The other theoretical dichotomy is a more recent debate between formalists and substantivists. Formalists suggest that the economy should be viewed (and thus studied) as a separate entity from other societal structures, whereas substantivists view the economy as embedded in the social, and thus inextricably cultural (Reger, 2005). Recently, however, both of these dichotomies have been abandoned in favor of a pluralistic approach that does not view the ancient economy as a monolithic entity which can easily be described and categorized using a singular framework (Reger, 2005). Due to the focus of the traditional large overarching theories on subsistence and self-sufficiency, there has been minimal focus on markets or production until recently (Harris, 2002; Margaritis, 2016). If markets and production were considered, the discussion was limited to evidence surrounding their existence and typology, rather than a discussion of the role they played in the economy (Harris & Lewis, 2016). Current studies of the ancient economy address questions regarding the definition of an economy, as well as determining what data can provide insights into these questions (Archibald, 2005). Understanding the economy is important as it is entwined with the social, ethical, and cultural norms of a society (Archibald, 2005).

3.3.1 Animals in the Religious Economy

Scholarship on Greek religion has tended to focus on the ubiquity of the sacred in ancient Greece which, although important, can mitigate the role of the sacred in the economy (Chankowski, 2011). Animals would have played a central role in the religious economy through their importance in animal sacrifice, which incorporates the supply of animals, the consumption of animals, and a potential market for selling by-products of animal sacrifice. Some sanctuaries had organized markets (Ekroth, 2019). Other important aspects of the religious economy include the purchase of raw materials, craftsmen, and contracts for construction (Chankowski, 2011).

3.3.2 Animals in the Domestic Economy

Traditional understandings of households and their function in ancient Greece stem from analyses of written records, combined with estimations of mortality rates, age at marriage, residence pattern, and mean household size (Gallant, 1991). Historically, there was limited archaeological interest in the domestic sphere with "ambivalent attitudes toward and selective treatment of domestic assemblages" (Ault & Nevett, 1999, p.43). When domestic contexts were investigated, the analysis tended to be descriptive and limited to the individual identification and typology of artifacts (Ault & Nevett, 1999; Nevett, 2005). This, however, changed with the implementation of New Archaeology, which uses data to ask a broader range of questions than previously examined. More recent studies have focused on space use and distribution within the domestic sphere with an emphasis on contextualizing the material remains (Nevett, 2005).

The household maintains a complex role in the economy as it functions both as a producer and as a consumer (Gallant, 1991). As such, it can be expected that the household will produce goods for both internal and external consumption (Cahill, 2005). House and workshop were often the same place; in fact, evidence of the production of goods is common archaeologically, especially in well-off households (Cahill, 2005).

3.3.3 Animals in the Market and Subsistence Economy

Until recently, the focus of studies on the Ancient Greek economy has been subsistence with less emphasis on the market economy (Margaritis, 2016). As previously mentioned, meat and other secondary animal products from sacrificial victims could be sold either at the sanctuary or at a market.

Discussion of the subsistence economy has historically focused on self-sufficiency of the home as a single entity (Margaritis, 2016). This has changed recently as scholars become increasingly interested in how the subsistence economy functioned and was impacted by cultural factors. Subsistence is linked to the economy as it revolves around the management and mobilization of resources (Barker & Gamble, 1985; Russell, 2012). From this perspective animals used for power, mobility, and meat/dairy can all be considered part of the subsistence economy.

3.4 Chapter Summary

This chapter provided an overview of animals in ancient Greece focusing on their importance in ritual and in the economy. Animal sacrifice is important to consider because of its impact on the zooarchaeological record. Scholarly approaches to animal sacrifice have, over time, transitioned towards understanding sacrifice as a fluid category that needs to be considered as part of a larger ritual framework. I discussed the different types of animal sacrifice, when and why the different types were used as well as the importance of these differences in zooarchaeological assemblages. Although animal sacrifice can be difficult to observe in the archeological record, the type of sacrifice and how the meat was treated post-sacrifice can be determined. There has been scholarly debate regarding consumption of sacrificed animals, primarily with respect to where the meat would be eaten; the presence of sacrificial meat outside the *temenos* of a sanctuary makes interpretation more difficult.

4 Animal Husbandry

This chapter will present an overview of animal husbandry, building on the definition from the introductory chapter. I will provide an overview of domestication and the identification of domesticated animals as it relates to animal husbandry, a review of the literature focusing on evidence for different practices and debates surrounding animal husbandry and agriculture in the literature. This will provide the baseline for conceptualizing ancient pig management strategies.

The relationship between humans and animals has been extensively studied using a number of different methods. Zooarchaeological studies initially emerged with a focus on quantitative methods including taxonomic categorization, aging methods, metrical analyses, and studies of bone modification (Makarewicz, 2016). Zooarchaeological studies of human-animal interactions came later, employing a combination of quantitative and qualitative approaches (Makarewicz, 2016). Depending on the disciplines involved and the goals of the research, various approaches have been used by zooarchaeologists. Cassidy (2007) suggests that different fields approach animal studies in varying ways depending on the questions being asked; for example, geneticists approach domestication differently than psychologists. Recent advances in archaeological thought consider animals, especially domestic animals, as having “complex social lives” (Makarewicz, 2016). Embedded in these theories is the idea that animal use is linked to the broader sociopolitical environment and that human-animal relationships change as a society and its economy evolve (Guiry et al., 2015). This makes the study of animal husbandry in the past a fruitful endeavor as it has the potential to reveal culturally significant information about humans, animals, and the interactions between the two.

4.1.1 Domestication

Important questions in the zooarchaeology of human animal-relationships include how domestication can be characterized from skeletal remains and where the earliest sites of animal domestication were. There are two major approaches to understanding domestication: biological and social. Biological approaches conceptualize domestication as either an act of human control, emphasizing the notion of a human-nature dichotomy, or a symbiosis with human and animals as equal partners (Russell, 2002). Conversely, social approaches favor the importance of changes in human-human and human-animal relationships as central in understanding domestication (Russell, 2002). Recent archaeological thought problematizes historical understandings of domestication suggesting that domestication, at least initially, is unlikely to be an intentional act (Larson et al. 2011). Domestication, however, remains an important and highly studied concept in zooarchaeology.

Generally, domestication is the set of processes by which control over the reproduction of animals or plants is assumed by humans (Vigne, 2011). The motivations resulting in domestication were highly varied, resulting in a gradient of relationships between human and animal societies from anthropophily to pet ownership (Alves, 2016; Vigne, 2011). Depending on how researchers view the processes of domestication and what constitutes a domesticate, organisms at different places along this relationship gradient can be determined to be "domesticated" (Vigne, 2011). Changes generally seen in animals following domestication include decreased aggressiveness, increased fertility, decreased sexual dimorphism, shortening of the face, decreased braincase volume, new coat colors, and voice changes (Vigne, 2011). The particular changes seen as well as the speed and extent of change vary depending on the animal species and the human-animal relationship involved (Vigne, 2011).

Sus scrofa is the only *fully* domesticated porcine species (Larson et al., 2011) and likely originated in South East Asia (Ruvinsky, et al., 2011). There are two competing models of pig domestication: i) domestication in the early Holocene in geographically distinct regions including the Near East and China and, ii) additional independent European domestication alongside the early Asian domestications (Larson et al., 2011). It appears, based on paleogenetic evidence, that the second model is more likely with subsequent introgression between the European and Asian clades (Giuffra et al., 2000).

4.1.1.1 Identifying Domesticated Pigs in the Zooarchaeological Record

The identification of domesticated pigs has been a subject of great interest to zooarchaeologists. Identifying domesticated animals zooarchaeologically can be difficult as many key indicators, including behavioral and soft tissue changes, are not visible skeletally meaning alternative methods have to be used. Ancient DNA (aDNA) analyses has proven to be effective for identifying the remains of domesticated animals (Bar-Gal et al., 2003; Horsburgh, 2008; Yang et al., 2008) and for studying soft-tissue phenotypic traits like coat color (Ludwig 2009). aDNA studies have provided valuable information regarding pig domestication, including evidence for multiple local domestications and for subsequent population movement and introgressions between domesticated and non-domesticated pigs (Krause-Kyora et al., 2013). aDNA is not commonly used, however, due to cost and preservation issues. Traditionally, size is used to identify domesticated pigs with larger elements being inferred to belong to wild animals and smaller being identified as domesticated animals (Evin et al., 2014); these metric approaches have been applied to skeletal (Evin et al., 2014; Wang et al., 2015) and dental (predominately third molar) (Cucchi et al., 2009; Cucchi et al., 2011; Evin et al., 2013) remains.

Odontochronology and other non-metric dental indicators have also been used (Pike-Tay et al., 2016; Pike-Tay & Ma, 2013). Stable isotope analyses have been used to detect changes in diet that may be indicative of domestication (Balasse et al., 2016; Hu et al., 2009).

4.2 Animal Husbandry in Greece

Animal husbandry in Greece has been studied bioarchaeologically, via written evidence, and through historical and modern analogy. There is little evidence of husbandry iconographically, with most depictions of animals being related to myth or sacrifice. Despite these efforts, knowledge of Greek animal husbandry in the past is limited as the available evidence is not always clearly indicative of the husbandry practices used (Isager, 1995).

4.2.1 Bioarchaeological Studies

Examining animal husbandry through bioarchaeological methods is becoming increasingly common. Isotopic analyses have been used to examine birth seasonality (Balasse et al., 2012; Frémondeau et al., 2012), the introduction of foddering regimes (Chen et al., 2016), and other aspects of the animals' diets (E. J. Guiry et al., 2015; Makarewicz, 2014). Although pig husbandry has received increasing attention in archaeological research in regions like the South Pacific (Shaw et al., 2009), it has not yet been intensively studied in Greece.

There are few bioarchaeological studies of animal husbandry in Greece. Faunal data can be used as comparative information in isotope studies of human diets, with isotopic variation within animal species sometimes considered to be due to differing husbandry practices (see Chapter 6 for a review of the isotopic literature). As discussed in Chapter 3, zooarchaeological methods have been used in studies of animal sacrifice, however, this type of study is more focused on the identification of sacrifice rather than the animal husbandry practices used to supply the victims.

Of the zooarchaeological, bioarchaeological, and archaeological studies of animal husbandry in Greece, most focus on the Neolithic and Bronze Age. Although these studies of earlier eras inform us about animal husbandry in those time periods, they are not directly applicable to Hellenistic Thessaly, just as we cannot assume that modern and ancient practices were similar (Forbes, 1995).

4.2.2 Written Evidence

Written evidence, as previously mentioned, can be difficult to decipher as the reliability of the ancient author can often be called into question. This is specifically an issue in Thessaly as many of the sources are Athenocentric. Animal husbandry in written texts is contentious as there is extensive mention of animals in the literature, but fitting it together is difficult; unsurprisingly, much of what is known is highly fragmentary. A number of authors, including Hesiod (Hes. *WD.* 422-447; Hes. *WD.* 590-607) and Xenophon (Xen. *Ec.* 17.6), discuss agriculture but not livestock practices.

Aspects of pig husbandry are noted by a number of ancient authors from historians to poets. The Odyssey references pigs in association with Odysseus' swineherd Eumaios; the pigs are kept in sties and an all-around enclosure (Hom. *Od*. 14.48-71). Aristotle mentions pig fattening and breeding regimes in Historia Animalium (Aristot. *Hist. An.* 8.6). Pliny, a Roman discussing Greek diet, discusses the 50 flavors of pigs (Plin. *Nat*. 8.77). There are, however, no direct discussions of husbandry practices in the literary record.

4.2.3 Ethnography and Modern Analogy

Modern analogy, through ethnographic methods, allows researchers to examine specific practices by questioning and observation of modern people. This is beneficial as researchers can see the practices “in action”, increasing the understanding of practices invisible in the archaeological record. Caution must, however, be taken as modern practices cannot be assumed to directly reflect practices in the past. When approached correctly, analogy can be a beneficial source of information (Wylie, 2002). Ethnographers have the advantages of being able to interact directly with modern human communities, observe practices and materials not visible in the archaeological record, and ask people for clarification as to why things are done a certain way. There are, however, major issues with relying on modern analogies, including differences in technology, economy, and population structure. As discussed by Forbes (1995), ethnographic accounts may be biased toward studying the most visible and distinctive forms of husbandry, which may not actually be typical. Finally, ethnographic accounts, like all studies, can be biased in terms of what data is collected and the specific interests of the researchers.

Most ethnographic work on pig husbandry practices is from the Pacific Islands and southeast Asia. Studies of this type are less common in Europe due to the perception that management practices have changed so extensively from ancient times that they are not relevant (Forbes, 1995). Three recent ethnographic studies have been completed in the Mediterranean region, though: in Sardinia, Greece, and Iberia.

The ethnographic work in Sardinia in 2005 suggested that although large herds (i.e. up to 400 animals) were once seen in Sardinia they are no longer economically feasible, resulting in smaller herds of 20-40 pigs (Albarella, et al., 2011). Of these animals, only 1-3 will be boars, a few will be piglets, and the rest will be castrated males. Only the males were reported to be sterilized. The local people live in villages in the valley with the pigs living on the plateaus. The herders drive up to care for them; prior to cars, men would hike to the plateau and stay for approximately a week to take care of their herd. Due to the location of the animals, most are free ranging with limited foddering in the winter (with a primary goal of keeping the pigs used to human presence) and heavier foddering in the summer when food is scarce. The pigs are typically slaughtered between one and three years of age with an exception being a new practice of killing suckling pigs around 1-2 months of age.

Ethnographic studies across Greece took into account different management practices and tried to get a survey of both extensive and intensive pig husbandry practices (Halstead & Isaakidou, 2011). The size of the herd differed between management focused on breeding and fattening: breeding could involve substantial herds whereas fattening would focus on 1-2 yearlings. Males were castrated at a few weeks of age unless chosen for reproduction; there is no mention of sterilization of females. Pig husbandry was a part-time endeavor with many herders taking it as a part-time job to make extra money. Unplanned interbreeding with wild boars was reported to have increased in recent years due to a decline in agricultural cultivation in some regions allowing pigs to roam free. Pigs foraging with herdsman were reported to walk up to a few kilometers a day – with some herdsmen including a few pigs in their transhumant management of sheep and goats. There were no reported cases of pig herd transhumance. The diet of extensively managed pigs seems to vary by season in quality and quantity; pigs graze on acorns, leaves, roots, worms, and crop processing waste with fodder provided only in dry summers, or as an incentive to return “home” after free ranging. The diet of household pigs could look similar to that of extensively managed pigs as the pigs would graze or be fed acorns when available; however, they also would be fed weeds from gardens, by-products of cheese making, and spoiled surplus from gardens and orchards, and were noted to consume as much grain (typically maize or rye) as an adult human. The pigs were reported to be slaughtered predominately as yearlings, however, sows used in reproduction were kept until they could not provide enough milk to suckle (4-5 years).

In Iberia (data collected in 2008), the size of the herds was larger with greater fluctuation throughout the year (Hadjikoumis, 2012). Males comprised less than 20% of the herd (with high percentages of males being seen in smaller herds) and 80-90% being yearlings or younger. Except for those used for reproduction, all pigs were reported to be sterilized at a young age (there is no mention of sex-specific practices). Most herders had at least one “free range” herd and one “semi-free-range herd”. The difference between these herds was human intervention: “semi-free range” herds were typically supplied with more food whereas “free-range” animals fed exclusively on wild resources for most of the year with supplementation in the spring. Most pigs were killed at one year of age; this timing was partially dictated by law.

Overall, these ethnographic studies of pig husbandry show the diversity of methods available and used in modern communities. There is a suggested difference in diet between extensively and intensively reared pigs. However, diet also seems to be tied to a number of external factors, meaning that diet is not an absolute indicator of management style and could be susceptible to change.

4.3 Pig Husbandry and Models of Ancient Agriculture

There has been a debate in Greek (bio)archaeology regarding agricultural methods employed in ancient Greece. These often tie into issues of scale and models of pastoralism. Although not directly related to pig husbandry, the various models of agricultural practice have implications for how land, crops, and animals were managed. There are two predominant models of ancient agriculture proposed in the literature. As reviewed by Hodkinson (1988), the *ethnographic model* suggests alteration of cereal crops with fallow fields with a distinct and fundamental separation between farming and husbandry, and the *Halstead model* suggests small scale gardening with crop rotation and regular manuring resulting in availability of summer fodder. The existing models relate more to agricultural practices and debates on transhumance of sheep and goats than on pig husbandry. Agricultural systems do, however, interact with the types of husbandry utilized.

We should be wary, however, of seeking an overarching model of animal husbandry in ancient Greece as such models oversimplify regional cultural and economic differences. Although there would likely have been prescribed outlines of different ways to rear animals, individual households would likely have exploited animals in different ways that reflected their particular goals, set against their specific circumstances (Forbes, 1995).

4.4 Chapter Summary

The information on pig husbandry from various lines of evidence does not provide a distinct model of pig husbandry in Greece but instead a series of thoughts on potential husbandry practices. These are, of course, dependent on the perceived utility of pigs and the purpose of the animals (e.g. there is a dichotomy between pig husbandry practices used for pig breeding and pig fattening). It has been suggested that owning animals was a practice of elites with the main goal being wealth generation (Forbes, 1995; Hodkinson, 1988; van Wees, 2009). Overall, the evidence highlights the complexity of animal husbandry practices suggesting a fluid, and complex repertoire of management styles. It also, however, provides a number of possible ancient approaches to animal husbandry that can be explored through stable isotope analysis.

5 Kastro Kallithea

Kastro Kallithea is a city dating to the Hellenistic period (323-31 BCE) in Thessaly, Greece. The site is located in the province of Larissa at the utmost western section of the coastal Plain of Almiros in the region of Achaia Phthiotis in Thessaly (Figure 5.1). The site was identified as the ancient polis Peuma by the German scholar Friedrich Stählin based on topological features that matched inscriptions of a polis of the same name (Stählin, 1914). This identification, however, is not definitive so the site is called Kastro Kallithea based on its proximity to a nearby modern village Kallithea. Since 2004, archaeological investigations at Kastro Kallithea have been conducted cooperatively by the Ephorate of Antiquities in Larissa and the University of Alberta, under the joint direction of Sofia Karapanou (Ephorate of Antiquities, Larissa) and Margriet Haagsma (Department of History and Classics, University of Alberta). Systematic research has also occurred at nearby Halos, Demetrias, Phthioitc Thebes, and Goritsa (Tziafalias et al., 2006); however, these are mainly coastal sites and little work has been done on interior sites such as Kastro Kallithea.

The earliest material found on the site dates to the Late Classical period, however, much of the material appears to be Hellenistic (Haagsma et al., 2019; Surtees et al., 2014). Although there are earlier Iron Age tombs found on the hill on which the site is located, there is no evidence of habitation earlier than the Late Classical (Surtees et al., 2014). The main occupation phase dates to the late 4th to 2nd centuries BCE (Haagsma et al., 2019). In the late 3rd to early 2nd century BCE, there appears to have been a reorganization and shift in occupation of the site, with the agora being abandoned (Haagsma et al., 2015; Rupp et al., 2012). Excavations suggest an overall occupation period of over 200 years, ending with the site being gradually abandoned in the later Hellenistic period (Haagsma et al., 2015).

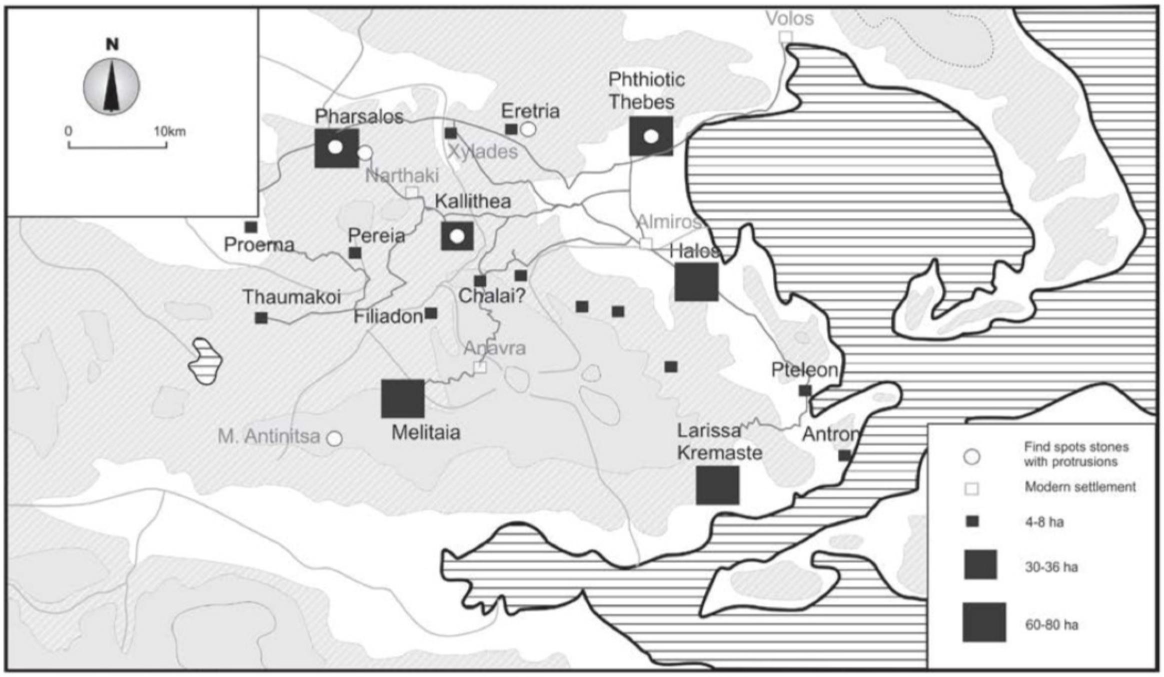

Figure 5.1: Map of Achaia Phthiotis with important sites identified. Figure from Haagsma (2015).

5.1 Site Layout

The site of Kastro Kallithea covers 34 hectares (Haagsma, 2014). The entire city, with the exception of the acropolis, is laid out on a grid system (Rupp, 2007) (see Figure 5.2). The orthogonal grid plan divides the city into regular housing blocks of 38-45m^2 (Haagsma, 2014). The streets measure 3.7m in width and avenues 5.8m in width on average (Rupp, 2007). The polis appears to have had residential, public, religious, and, potentially, military zones (Surtees et al., 2014). The site includes an agora with monumental stoa, defensive walls, and city gates (Haagsma, 2014). Most of the faunal material comes from Building 10, a large residential building, however, animal remains have also been recovered from test pits and the Acropolis Building 1.

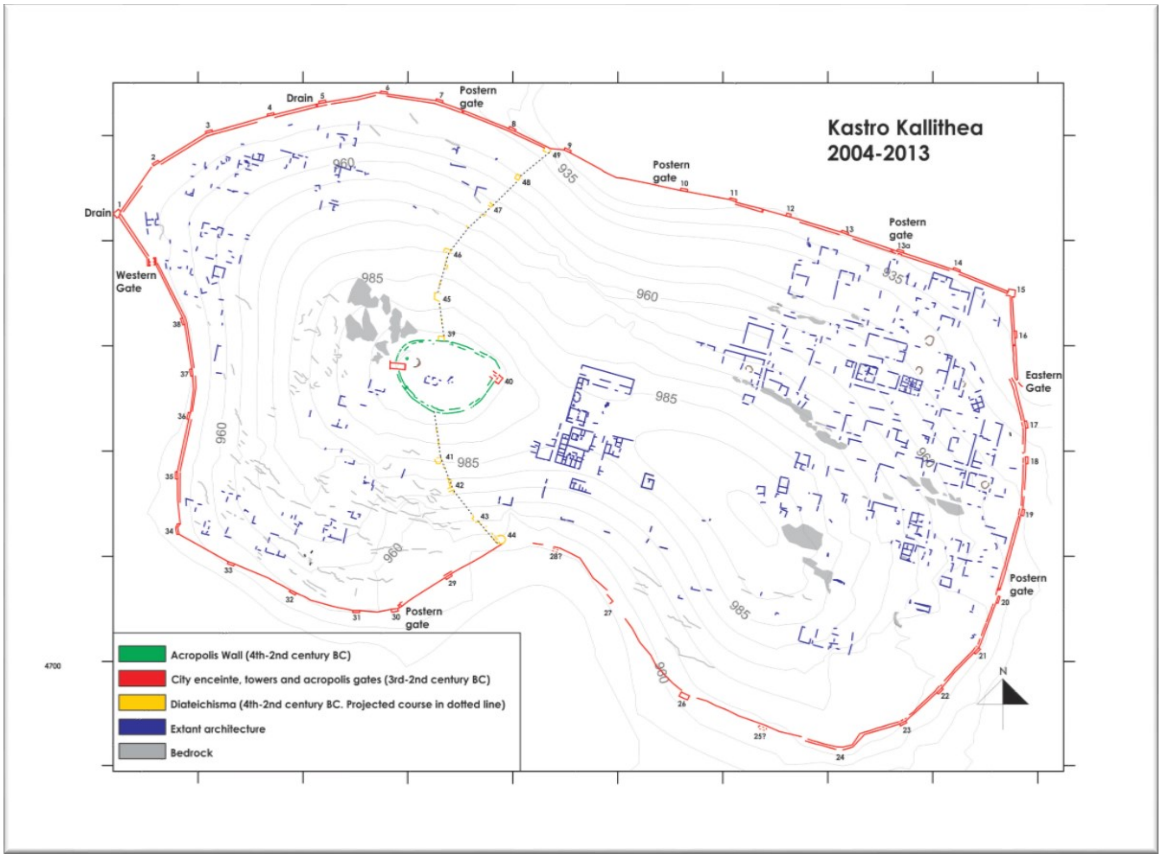

Figure 5.2: Map of the site of Kastro Kallithea. Figure from Haagsma (2015).

5.2 Project Goals and Research

The main goals for the Kallithea project are to gain insight to the political, social, and economic organization of the polis (Rupp, 2007). Integral to this is identification of the organization, development and transition to a Hellenistic domestic economy (Tziafalias et al., 2006). Thus far, this has been studied through the lens of domestic architecture, settlement archaeology, and conventional faunal analysis (e.g. Haagsma, 2014; Surtees et al., 2014).

Research at the site has focused on how the polis developed, the role it played in the changing political scene of the region, and why it was abandoned (Rupp, 2007). The survey project, published by Surtees and colleagues (2014), suggests that the increase in military and political hostilities in the region (described in Chapter 2), combined with potential economic motives, led to the initial construction of the site. Analyses of the defense system of the polis, containing three levels of defense — an outer circuit wall, a *diateichisma* (which divides the city into two sections), and the acropolis wall — have been used to suggest significant organizational abilities, a polis-wide agenda, and strong financial resources (Chykerda et al., 2014; Chykerda, 2010; Haagsma et al., 2019; Surtees et al., 2014).

Current studies at Kastro Kallithea consist of a stable isotope analysis of sheep and goat remains being conducted by Katherine Bishop (Bishop et al., 2019). Her study involves examining transhumance and pastoralism via incremental strontium, oxygen, and carbon isotope analysis of molar enamel.

Currently there is a paucity of published evidence for the economic structure of the community living in the city (though see Haagsma et al. (2019)). Excavations have revealed at least one metallurgical workshop that is potentially attached to a house (Surtees et al., 2014). The large number of iron slags recovered also suggest metal working occurred at the site (Rupp, 2006). In the domestic sphere, the volume of loom weights and grindstones recovered from Building 10 has been used to suggest the importance of domestic work in the economy (Stamatopoulou, 2011).

5.3 Building 10

Building 10 was originally, a domestic structure, owned by a wealthy family (Surtees et al., 2014). The building was initially noted and cleaned by a Greek archaeological team in 2005 with excavations beginning in 2007 (Whitley et al., 2007). It has been suggested that Building 10 may not have been part of the initial construction of the site but instead was built slightly later

(Rupp et al., 2012). Based on the presence of two small pits, it is thought that Building 10 was looted in modernity, but the extent to which this took place is unknown (Whitley et al., 2007).

The goals of the Building 10 excavation were to obtain insight into domestic economy, to chart changes in household and city organization over time (Rupp, 2011), and to move away from the Athenocentric understanding of domestic spaces that currently prevails (Haagsma et al., 2015).

The rooms in Building 10 (Figures 5.3 and 5.4) surround a central peristyle courtyard (Rupp et al., 2016) suggesting, perhaps, a Roman influence (Haagsma et al., 2015). The presence of a flat stone in Room 10 with postholes to support wooden stairs suggest it was a two-story building. A second story complicates determining context as artifacts may have fallen from the second floor as the building collapsed.

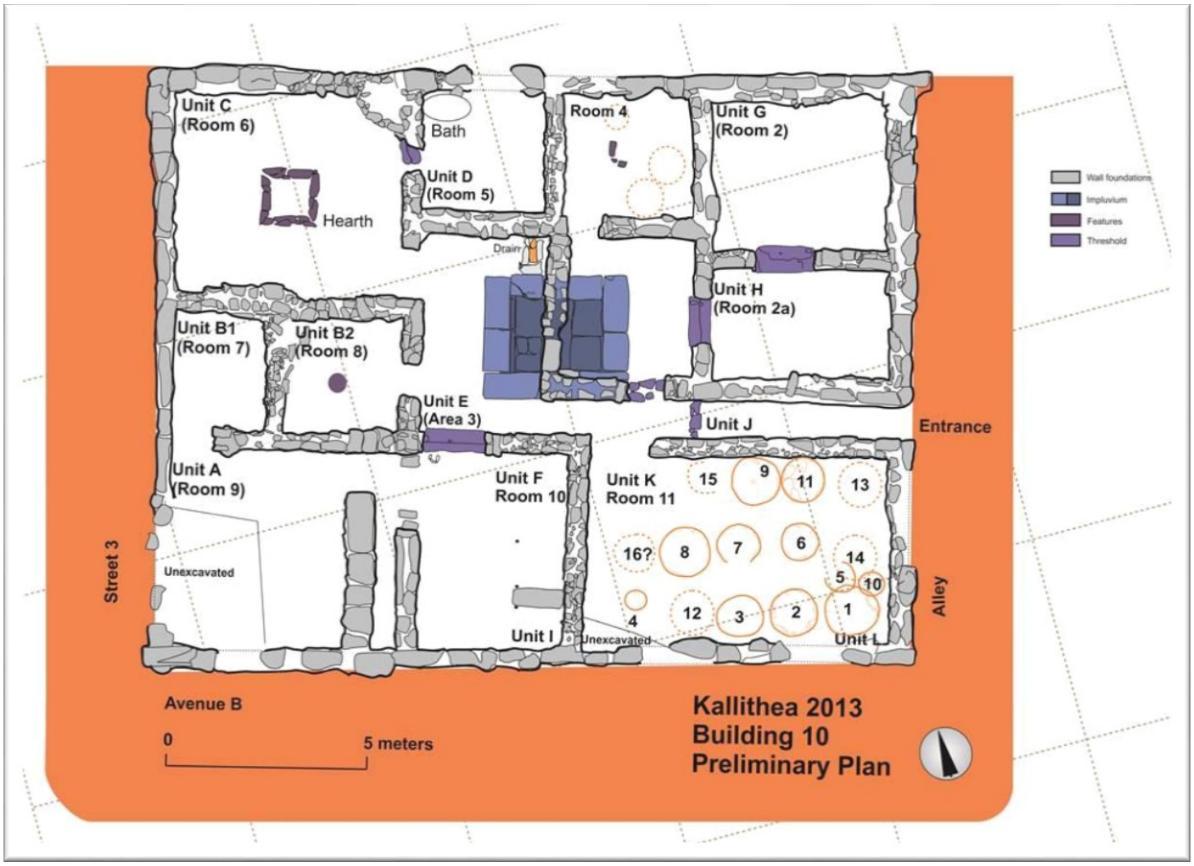

Figure 5.3: Map of Building 10 first occupation. Figure from Haagsma and colleagues (2015).

Figure 5.4: Arial photograph of Building 10. Figure from Haagsma and colleagues (2015).

Building 10 is thought to have been constructed in the late 3rd century BCE and abandoned later in the 2nd century BCE (Haagsma et al., 2019). There were at least two occupation phases of Building 10 (Rupp, et al., 2012). It is only possible to definitively distinguish the two phases in Room 4 and the courtyard, where the material is from the second occupational phase, but Rooms 2, 2a, and the upper portion of Area 3 were also part of the second occupational phase (Haagsma et al., 2019). In the second phase, Room 4 was used primarily for cooking, whereas, in the first phase, the internal courtyard would have been the locus for most of the cooking as it contained the main hearth. The second occupation phase involved a series of renovations (or possibly reconstructions depending on the state of the building) including a re-organization of space (Rupp et al., 2012). The re-organization included the formation of two new walls (K and O) which created a new room and either cut the courtyard in half or, possibly, eliminated it (Rupp et al., 2012) (Figure 5.5).

As previously noted, the occupants of the building appear to have been wealthy; however, the source of the wealth is unclear as there is no distinctive household industry (Rupp, 2011).

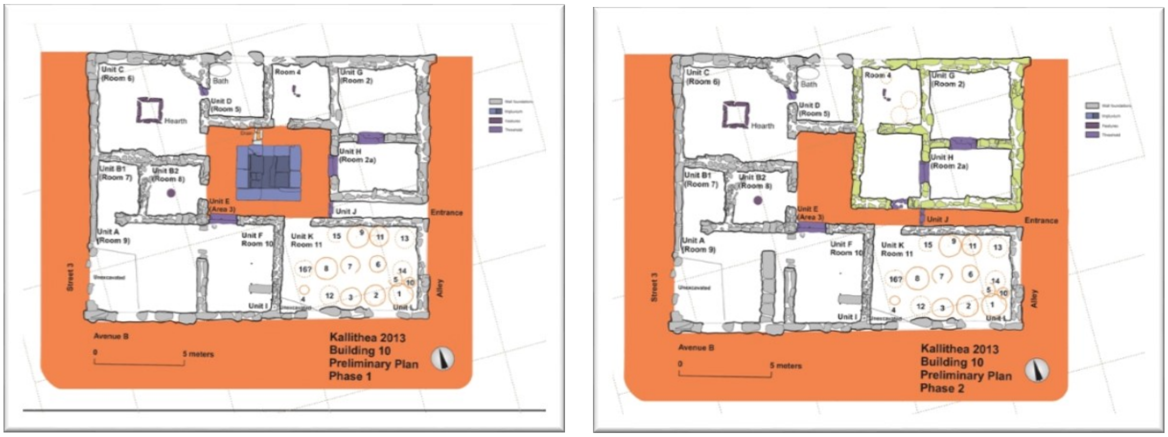

Figure 5.5: Maps of the Building 10 during first phase of occupation (left) and during the second phase of occupation (right). Figure from Haagsma and colleagues (2015).

5.3.1 Building 10 Contexts

There is no overarching synthesis of Building 10 as no central monograph has yet been published on the material from Kastro Kallithea, though an initial summary is available in the site's Guide Book (Haagsma et al., 2019). It is, however, important to have a general understanding of the different contexts from which the faunal remains were recovered. A storage room (Room 11), an andron (Room 2), a bathroom (Room 5), and a larger living area (Room 6) have all been identified in Building 10 (Haagsma et al., 2019). Domestic cult activity is suggested by the presence of remains in and surrounding the hearth as well as in other rooms in the house (Haagsma, 2014). One example of cult activity is found in Room 6, which has a stamnoid *pyxis* decorated with a coiling snake, with burnt bones and ash found inside (Haagsma, in press). The following sections review the contexts based the information currently available.

Room 2 was used in both occupational phases of the site. Elaborate threshold walls plastered with patterns of red, blue, yellow, black, and white colored rectangles have been identified as being from the first occupation (Rupp et al., 2016). Based on the elaborate walls, it has been suggested that Room 2 was used for receiving visitors (Rupp et al., 2016). The large number of loom weights recovered from the room contradicts this theory, but the loom weights may have fallen from the second floor (Rupp et al., 2016) or, alternatively, were from the second occupation of the site (Haagsma et al*.,* 2015).

Room 4 was also used in both occupations of the building. It contains a hearth that would likely have been the main hearth in the second occupational phase (Haagsma et al., 2019). Additionally, there were *pithoi* found in the room which were probably in use during the second occupation of the building.

Room 5 was only used during the first occupational phase. The floor appears to have been covered with waterproof pink plaster with white plastered walls and a drain running to the courtyard (Rupp et al., 2012). There are at least 28 *unguentaria* (small ceramic or glass bottles often used for storing oil or other liquids; in this case, thought to hold perfume) found in the room (Wiznura, forthcoming). Since this room also contained fragments of a bathtub, it is suggested that that Room 5 functioned as some type of bathroom. Interestingly, there were also 40 loom weights recovered from the room, but it has been suggested that these may have fallen from storage on the wall (Haagsma et al*.,* 2015).

Room 6 has a formal square hearth that has been linked to domestic cult activity in the first occupational phase (Haagsma et al*.,* 2015). Additionally, it contained a cupboard and a refuse pit. The room has been interpreted as a private family room.

Twelve intact *pithoi* were found *in situ* in units K and L (Room 11) along with a number of other broken pithoi (Rupp et al., 2016). These had an estimated total storage capacity of 14,202L (Haagsma, 2014). This type of storage capacity has not been observed in urban domestic spaces and is typically only seen at farmsteads (Haagsma et al*.,* 2015).

Area 3 was in use in both occupational phases, functioning as a courtyard with central pool in the first phase but, during the second phase, an L-shaped wall was built generating an additional room. The central pool was abandoned after the first phase.

5.4 Acropolis Building One

Acropolis Building 1 has not been fully excavated at this point. Two test trenches have been excavated (Figure 5.6) Although initial hypotheses suggested that it was built earlier than the rest of the city (in the Early Classical period), test trenches do not support this theory (Rupp, 2007; Whitley et al., 2007). The ceramics recovered date mainly to the Late Classical, Hellenistic, and Early Byzantine periods and suggest that the site was reoccupied (Rupp, 2007). Underneath and between the Hellenistic pottery fragments is a substantial amount of fragmentary animal bone (Rupp, 2007).

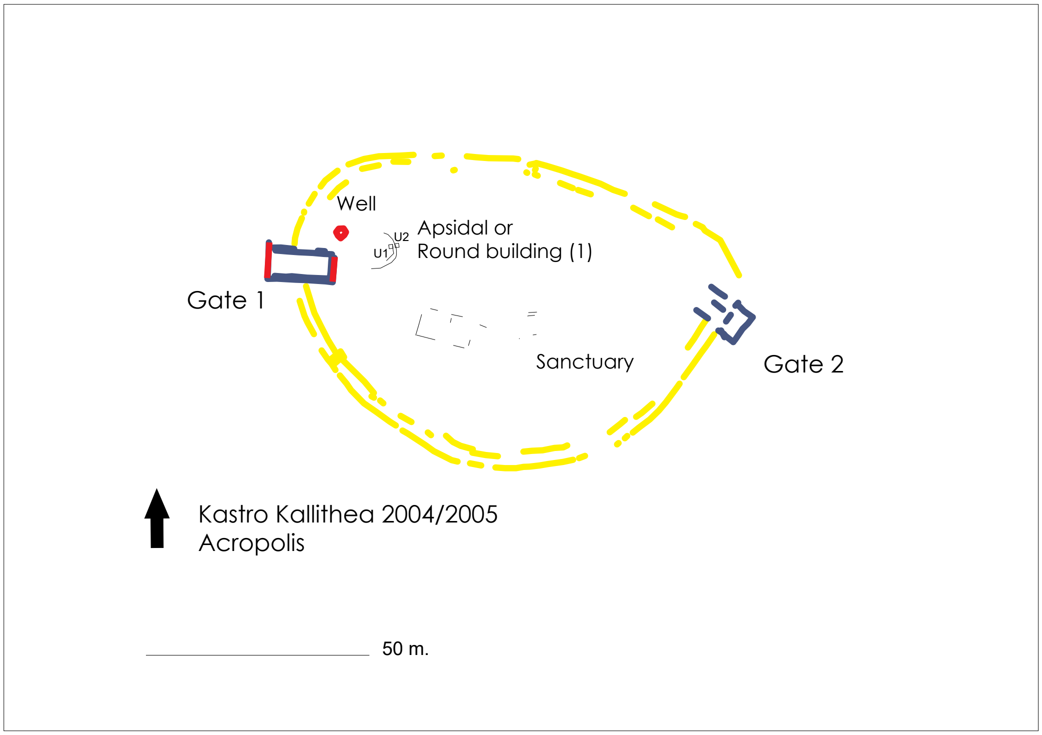

Figure 5.6: Map of Acropolis with Acropolis Building 1 and units 1 and 2. From Tziafalias et al (2006)

5.5 Faunal Material

The faunal assemblage was analyzed by Dr. Michael MacKinnon (Department of Anthropology, University of Winnipeg) – all species identifications including numbers used in NISP can be attributed to him. Initial analysis of the faunal material suggests that a farming economy predominated with an emphasis on wool and milk production (Haagsma, 2014). Animal products, although important, were a part of a bigger subsistence economy that included the cultivation of cereals, vines, legumes, nuts, and vegetables (Haagsma, 2014).

5.5.1 Describing Faunal Assemblages

Number of identifiable specimens (NISP) is an aggregate total number of identified elements in an assemblage. Faunal remains are identified as precisely as possible, ideally to the species level; this, however, is not always possible. NISP is a count of all the elements belonging to each species. There are inherent flaws with the measurement as it can overestimate the number of animals represented by the assemblage (Lyman, 2008; MacKinnon, 2014a); for example, all of the bones from a given species in an assemblage might belong to a single individual, leading to discrepancies regarding the importance to attach to a single element. Thus, NISP should be considered a quantitative method of describing a faunal assemblage rather than an absolute measure. A review of the advantages and drawbacks of NISP can be found in Lyman (2008). NISP, for these reasons, is not an ideal way to compare sites quantitatively; however, as long as its limitations are understood, and the conclusions drawn do not overstep the capacity of the method, it is a useful measure.

Minimal number of individuals (MNI) is another way to describe a faunal assemblage. Rather than an aggregate count of all the elements belonging to each species, the MNI describes the smallest number of individuals that could account for all the elements in a sample. This is calculated based on duplication of elements, differing age, or sex. This number is, by definition, the minimum number of individuals present and, thus, should not be interpreted as being representative of all the individuals in the sample. MNI was not used in this study as this data was not provided in the publications for the majority of the sites considered. Whereas NISP tends to overestimate the number of living animals an assemblage represents, MNI tends to underestimate. Although many studies include both MNI and NISP in their descriptions, it is not essential for this study.

5.5.2 Faunal Assemblage at Kallithea

The faunal assemblage at Kallithea, to date, is from the excavation of three structures: Acropolis Building 1, Building 5, and Building 10. Of the faunal remains recovered from these contexts, 1,466 fragments could be attributed to a particular taxon. More than 80% of the identified remains are from various domesticates, suggesting their importance from the perspective of diet and social relations. There is no noted bone industry in any of the excavated buildings, suggesting that the remains recovered were not discarded as waste from industry (MacKinnon, 2016).

Sheep/goat remains are predominant at the site, making up 57% of the total recovered identifiable remains and 71% of domesticates (Table 5.1, Table 5.2). Pigs make up the next largest percentage of recovered identifiable remains at 15% (18% of domesticates). This is followed by tortoise and red deer which each make up 7% of recovered remains. Dog and cattle make up 3% of recovered identifiable remains each; domestic fowl and hare each make up 2%, and equid, wild boar, and fish each make up 1%.

Based on the high percentage of wild, presumably hunted, animals, it is possible that hunting was an important contribution to the diet. However, the presence of wild animals in the archaeological record may, in fact, be due to differing butchery practices, processing techniques, and disposal norms if these differed from those for domesticated animals.

Pigs appear to have been preferentially killed as subadults or young adults. Subadults, especially piglets, have been identified as potentially being important sacrificial animals especially for small household or individual sacrifices due to their low cost (Ekroth, 2014b). Juvenile pigs are also the preferred sacrifice to specific deities including Demeter (Bookidis et al., 1999; Bremmer, 2006; Ekroth, 2014).

Table 5.1: NISP and % For the Whole Site

Species	***NISP***	***%***
Cattle (Bos taurus)	39	2.66
Sheep/goat (Ovis aries / Capra hircus)	836	57.03
Pig (Sus scrofa dom.)	218	14.87
Equid (Equus sp.)	12	0.82
Dog (Canis familiaris)	47	3.21
Domestic fowl (Gallus gallus)	29	1.98
Red deer (Cervus elaphus)	102	6.96
Fallow deer (Dama dama)	2	0.14
Roe deer (Capreolus capreolus)	9	0.61
Wild boar (Sus scrofa fer.)	14	0.95
Hare (Lepus europaeus)	29	1.98
Other bird (not domestic fowl)	13	0.89
Fish	10	0.68
Tortoise (Testudo sp.)	106	7.23

Table 5.2: NISP and % For the Whole Site, Domesticates Only

Species	***NISP***	***%***
Cattle (Bos taurus)	39	3.30
Sheep/goat (Ovisaries/ Capra hircus)	836	70.79
Pig (Sus scrofa dom.)	218	18.46
Equid (Equus sp.)	12	1.02
Dog (Canis familiaris)	47	3.98
Domestic fowl (Gallus gallus)	29	2.46

5.5.3 Building 10

From Building 10, 1,339 remains were recovered and identified. Of these, greater than 79% can be attributed to domesticated animals (Table 5.3, Table 5.4). The most numerous are, unsurprisingly, sheep and goat, which make up 56% of the identified remains and 71% of domesticates. Pigs make up 14% of the identified remains and 18% of domesticates. This is followed by tortoise which make up 8% of the identified remains.

Table 5.3: Building 10 NISP and %.

Species	***NISP***	***%***
Cattle (Bos taurus)	29	2.17
Sheep/goat (Ovisaries/ Capra hircus)	756	56.46
Pig (Sus scrofa dom.)	191	14.26
Equid (Equus sp.)	12	0.90
Dog (Canis familiaris)	47	3.51
Domestic fowl (Gallus gallus)	28	2.09
Red deer (Cervus elaphus)	96	7.17
Fallow deer (Dama dama)	2	0.15
Roe deer (Capreolus capreolus)	9	0.67
Wild boar (Sus scrofa fer.)	14	1.05
Hare (Lepus europaeus)	27	2.02
Other bird (not domestic fowl)	13	0.97
Fish	10	0.75
Tortoise (Testudo sp.)	105	7.84

Table 5.4: NISP and % for the B10 Domesticates

Species	***NISP***	***%***
Cattle (Bos taurus)	29	2.73
Sheep/goat (Ovisaries/ Capra hircus)	756	71.12
Pig (Sus scrofa dom.)	191	17.97
Equid (Equus sp.)	12	1.13
Dog (Canis familiaris)	47	4.42
Domestic fowl (Gallus gallus)	28	2.63

The deposition of the remains throughout the house suggests that deposition was approached individually rather than in a single isolated deposit (MacKinnon, 2016). This is attested to by the random nature of the depositions with remains being present throughout the whole house without any distinctive midden (MacKinnon, 2016). Lindenlauf (2000) suggests that sacrificial byproducts can be considered waste rather than sacred when one of three deposition types are present: a mixture of faunal and profane items in the same deposit, if the remains fulfil a practical purpose, or if the remains seem to be deposited carelessly in a practical structure. The remains recovered from Building 10 seem to fit the last option — uneven distribution, seemingly random deposits in a functional domestic space. Although all of the contexts from Building 10 are represented, a high volume of material was recovered from Unit B (Rooms 7, 8), Unit C (Room 6), Unit E (Area 3), and Unit K (Room 11) (Figure 5.7).

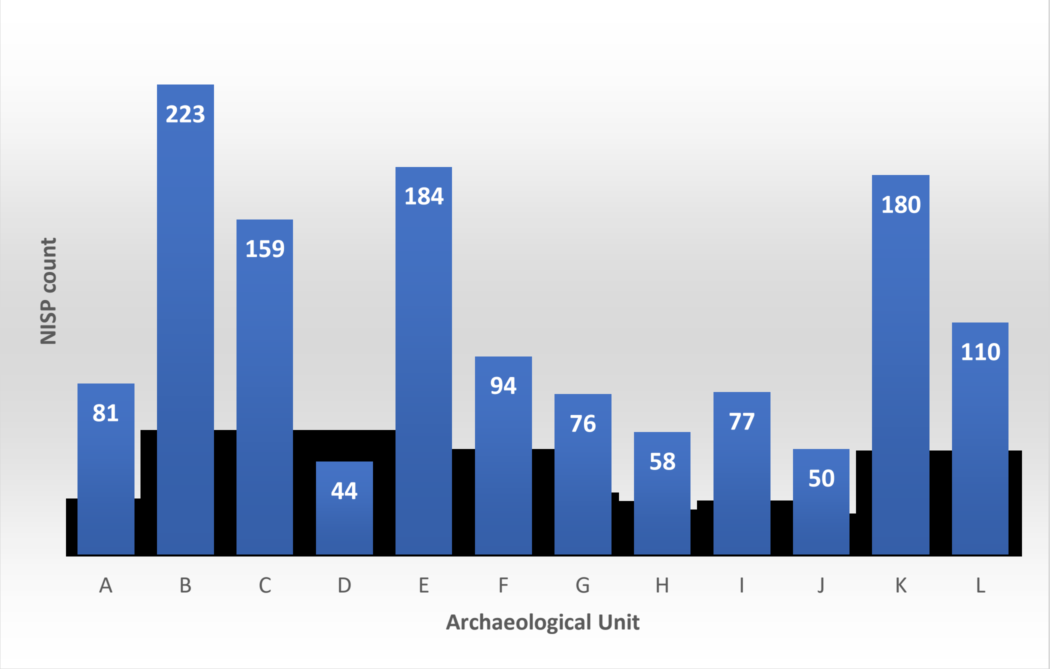

Figure 5.7: Faunal NISP by Unit Building 10. Adapted from MacKinnon (2016).

The assemblages of the early and later phases are similar in amount of material, the taphonomy affecting the bone, and the nature of the deposits (MacKinnon, 2016). The number of domestic taxa does increase slightly in the second phase (84.2% to 89.5% of the assemblage) (MacKinnon, 2016).

5.5.3.1 New Halos

An interesting comparison is the difference between Building 10 material from Kastro Kallithea and domestic contexts from New Halos. The polis of Halos ("Old" Halos) was destroyed in 346 BCE by a Macedonian army; however, a new polis with the same name ("New"

Halos) was built within 50 years (Reinders & Prummel, 1998). New Halos appears to have been abandoned after an earthquake in 265 BCE (Reinders, 2014). Both sites are Classical / Hellenistic Thessalian sites; however, Kastro Kallithea is landlocked whereas New Halos is coastal. New Halos is located approximately 30km east of Kastro Kallithea between the Almirós plain to the North and the Soúrpi Plain to the south, approximately 1.5km from Soúrpi Bay. There is a triangular upper part of the town and a rectangular lower town containing the residential space (Prummel, 2003). New Halos appears to have been a military site with most of the inhabitants being soldiers and their families (Prummel, 2003). Six houses have been excavated, and the evidence from this investigation suggests that the site was occupied for a short time, 302-265 BCE, before being destroyed by an earthquake and subsequently abandoned (Reinders & Prummel, 1998). All houses excavated had a similar layout including a courtyard, living room, two small rooms off the living room, and at least one additional room (Prummel, 2003).

The faunal assemblage from New Halos comprises the remains from six domestic contexts, representing some of the earliest zooarchaeological analyses in Hellenistic Thessaly. Reinders and Prummel (1998) proposed that large scale pastoralism was practiced at the site and argue for the presence of transhumant practices. The faunal remains from the site have been suggested to have been sacrificially killed at a sanctuary and then transported to the residential space for consumption (Prummel, 2003).

Interestingly, there are few fish bones at the site which is unexpected given the site's proximity to the water. As noted by Haagsma (2010), however, this does not rule out the possibility of fish being important to the diet; it simply means that few fish bones were recovered. Domestic mammals make up the second largest percentage of the faunal assemblage after marine mollusks at 37%. Of the domestic mammals, the assemblage is dominated by sheep/goat remains which make up 67%, followed by cattle at 23%, pig at 5%, horse at 4%, and dog at 1% (Prummel, 2003) (see table 5.6).

Table 5.5: NISP and % New Halos

Species	***NISP***	***%***
Domestic Mammals	322	36.67
Wild Mammals	18	2.05
Tortoise	13	1.48
Fish	1	0.11
Marine Molluscs	504	57.40
Terrestrial Molluscs	20	2.28

Table 5.6: NISP and % New Halos Domesticates

Species	***NISP***	***%***
Equid	13	4.04
Dog	4	1.24
Pig	16	4.97
Cattle	74	22.98
Sheep/Goat	215	66.77

When this assemblage is compared to the Kastro Kallithea material, several differences are apparent. The first is the proximity to water, reflected in the New Halos assemblage containing a higher proportion of marine mollusks (57.4% of the assemblage) than Kastro Kallithea (0% of assemblage) (see Figure 5.8). Kastro Kallithea has a higher frequency of domestic mammals (80%) and wild mammals (11%) than New Halos (37% and 2% respectively). When comparing the domesticates identified in the assemblages, the sites appear more similar with the major difference being the frequency of cattle and pig at the sites. Kastro Kallithea has fewer cattle (2.8% versus 23%) and more pigs (18% versus 5%) (see Figure 5.9).

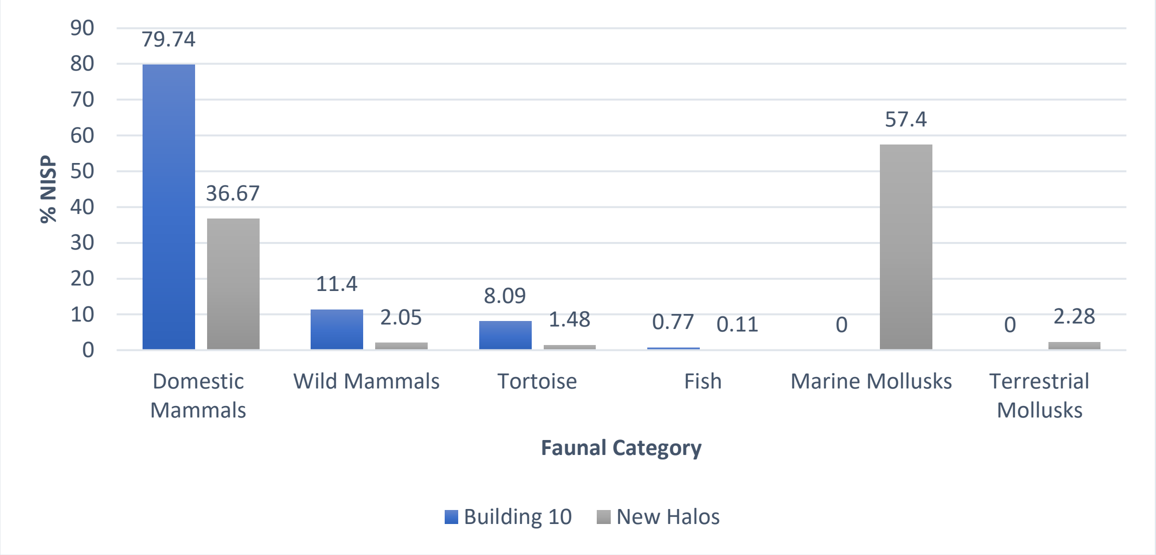

Figure 5.8: NISP frequency for domestic mammals, wild mammals, tortoise, fish, marine mollusks, and terrestrial mollusks between Kastro Kallithea Building 10 and New Halos.

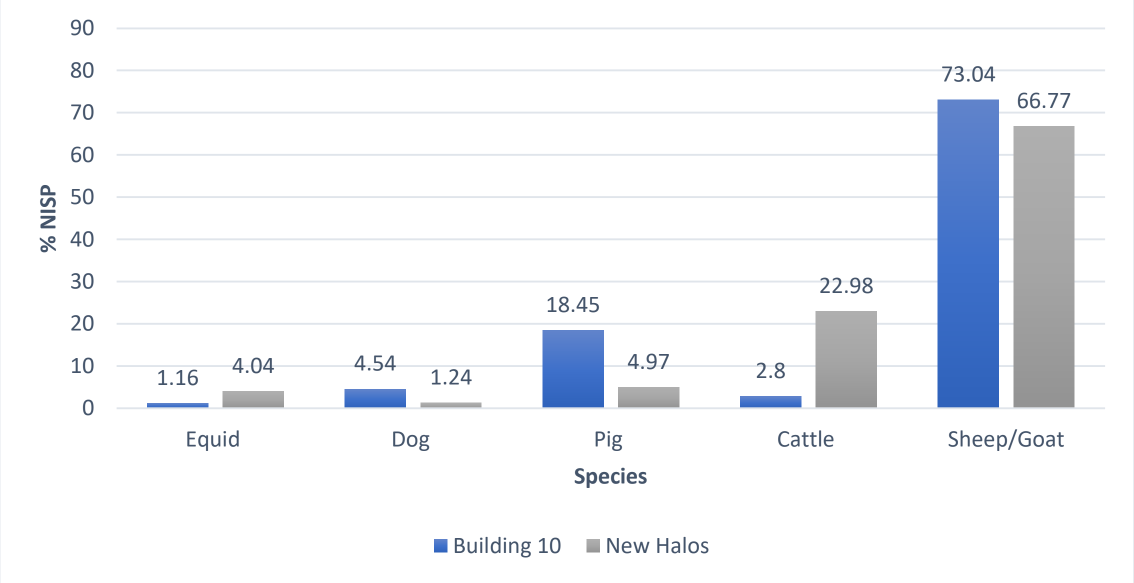

Figure 5.9: NISP frequency for horse, dog, pig, cattle, and sheep/goat between Kastro Kallithea Building 10 and New Halos.

5.5.4 Acropolis Building 1

The assemblage from Acropolis Building 1 at Kastro Kallithea is dominated by sheep and goat which together comprise 62% of the identified material and 67% of the identified domesticated material (Table 7, Table 8). This is followed by pigs, which make up 22% of the total identified specimens and 24% of domesticates, and cattle which make up 8% of total identified material and 9% of domesticates. With the exception of six fragments of red deer, two of wild hare, and a fragment of tortoise, the acropolis building is essentially represented by domesticated animals. This is expected as the skeletal material present is thought to be connected to animal sacrifice, in which domesticates would be expected to predominate.

Table 5.7: Kastro Kallithea Acropolis Building 1

Species	***NISP***	***%***
Cattle (Bos taurus)	10	8.13
Sheep/goat (Ovis aries/ Capra hircus)	76	61.79
Pig (Sus scrofa dom.)	27	21.95
Equid (Equus sp.)	0	0
Dog (Canis familiaris)	0	0
Domestic fowl (Gallus gallus)	1	0.81
Red deer (Cervus elaphus)	6	4.88
Fallow deer (Dama dama)	0	0
Roe deer (Capreolus capreolus)	0	0
Wild boar (Sus scrofa fer.)	0	0
Hare (Lepus europaeus)	2	1.63
Other bird (not domestic fowl)	0	0
Fish	0	0
Tortoise (Testudo sp.)	1	0.81

Table 5.8: Kastro Kallithea Acropolis Building 1—Domesticates

Species	***NISP***	***%***
Cattle (Bos taurus)	10	8.77
Sheep/goat (Ovisaries/ Capra hircus)	76	66.67
Pig (Sus scrofa dom.)	27	23.68
Equid (Equus sp.)	0	0
Dog (Canis familiaris)	0	0
Domestic fowl (Gallus gallus)	1	0.88

5.6 Chapter Summary

Kastro Kallithea is a Classical/Hellenistic site located in the Western aspect of the Plain of Almiros in Thessaly. The site has one major excavated structure, Building 10, which is where the majority of my samples are from (the others being from Acropolis Building 1). Building 10 had two occupational phases – the second occupation can only be definitively identified in Rooms 2 and 4. The first (and primary) phase of Building 10 occupation appears to be by wealthy owners based on the size of the house and artifacts recovered in excavation. Less is known about Acropolis Building 1 as excavations were limited to two test trenches. Overall, the faunal assemblage at Kastro Kallithea is dominated by domesticated mammals, of which pigs' skeletal remains make up 18%. I compared the faunal assemblage from Building 10 at Kastro Kallithea to the domestic structures from New Halos, a contemporary Thessalian city located by the sea. The two sites differed in the number of terrestrial mammals and marine mollusks, which can be explained by the proximity of New Halos to the ocean, as well as in percentage of pigs and cattle with Kallithea having more pig remains and New Halos having more cattle. Overall, however, the two *poleis* appear comparable regarding their faunal assemblages.

6 Stable Isotopes

This chapter will provide an introduction to stable isotopes and then focus on carbon and nitrogen isotopic systems including variation in autotrophs and heterotrophs. I will also provide an overview of the skeletal tissues that can be used in stable isotope analysis, and models of inclusion of carbon into bone collagen.

6.1 Introduction

Stable isotope analysis of bone or tooth tissue can provide a record of an individual's diet throughout life (Katzenberg, 2000; Lee-Thorp, 2008). Stable isotope values for many elements vary systematically in the environment, with different groups of organisms producing distinctive isotopic signatures (Müldner, 2005). These isotopic signatures allow us to distinguish between broad categories of resources in human and animal diets. In this review, carbon and nitrogen isotopic systems will be discussed separately because they are patterned in different ways, but this is purely for clarity as they are always considered together in dietary reconstruction.

6.2 Overview – Definition, Fractionation and Notation

As reviewed by Hoefs (2015), isotopes are atoms of the same element with differing numbers of neutrons, which results in the atoms maintaining the same chemical properties but with different atomic masses. In the environment, multiple stable isotopes of elements such as carbon, nitrogen and oxygen are present at different natural abundances. Although the differences in mass between isotopes are minor, they can impact how the atoms interact in chemical reactions and in physical processes such as evaporation. This can cause fractionation –

a change in isotopic content over the course of the reaction or process. Stable isotopes, unlike the radioactive isotopes used in some absolute dating methods, do not decay spontaneously.

Hoefs (2015) also discusses the essentials of isotopic notation and measurement. Briefly, isotopes are represented using the abbreviation for the element with the number of protons and neutrons (the atomic number) in superscript; this number changes based on the isotope being discussed. For example, oxygen is abbreviated "O" and its most abundant isotope, oxygen-16, has eight protons and eight neutrons and is written as ^{16}O. Stable isotope content of light elements such as oxygen is expressed as a ratio of the heavier isotope (more neutrons – e.g., ^{18}O) to the lighter stable isotope (fewer neutrons – e.g., ^{16}O). The ratio is compared to an international standard arbitrarily set at 0 and is reported in terms of departure from that standard in parts per mil (‰), the delta value (δ). A positive delta value indicates that the ratio of the heavier to the lighter isotope is higher than that of the standard; a negative value indicates that the ratio of the heavier to the lighter isotope is lower than that of the standard. When writing the delta value, the atomic number of the heavier isotope is used (i.e. $\delta\,^{\mathbf{18}}O$).

6.3 Carbon

The stable carbon isotope system can be used to distinguish between broad types of plants based on their method of CO_2 incorporation during photosynthesis, as well as between marine and terrestrial environments. Carbon has two stable isotopes with ~ 98.9% of global carbon being the lighter ^{12}C isotope and ~ 1.1% the heavier ^{13}C isotope (Farquhar et al., 1989). Although ^{12}C and ^{13}C are chemically interchangeable, they differ in weight with ^{13}C being 8% heavier than ^{12}C (Bütz et al., 2014). This small difference in weight is sufficient to cause differential participation of the two isotopes in reactions even at equilibrium (Bütz et al., 2014).

During early research on stable carbon isotopes, the international standard Peedee Belemnite (PDB), a marine limestone, was selected for reporting stable carbon isotope values. This standard was exhausted long ago and values are currently reported relative to the international standard Vienna Peedee Belemnite (VPDB), which has the same stable carbon isotope content at the original PDB (Long, 1995). The $\delta^{13}C$ value of this standard is arbitrarily set at 0‰. Since most biological material is depleted in ^{13}C relative to VPDB, biological samples such as plant and animal tissue usually have negative $\delta^{13}C$ values.

6.3.1 Carbon in Autotrophs

Variation in $\delta^{13}C$ values in producers – organisms that produce their energy through photosynthesis rather than through the consumption of other organisms – stems in part from differences between photosynthetic pathways in terms of their carbon isotope discrimination during the incorporation of CO_2 into plant biomass. Plant $\delta^{13}C$ variation reflects both the organism's carbon source and the photosynthetic pathway it uses.

6.3.1.1 Carbon Sources and Plant $\delta^{13}C$ Variation

Terrestrial, marine, and freshwater plants incorporate carbon from different sources. Terrestrial plants use atmospheric carbon in photosynthesis, whereas marine and freshwater plants use dissolved inorganic carbon from the surrounding water. This variation helps to explain the different $\delta^{13}C$ values typical of land, marine, and freshwater organisms.

Changes in the $\delta^{13}C$ of the atmospheric CO_2 a plant has access to will directly affect its tissue $\delta^{13}C$ values. Factors impacting the $\delta^{13}C$ of the CO_2 a plant can draw on include the canopy effect, which will be discussed later in this chapter. Additionally, the overall $\delta^{13}C$ value of atmospheric CO_2 has changed over time. Studies of ice cores, tree rings, and marine sediments show that there has been a decline of about 1.5‰ in atmospheric CO_2 since approximately 1850 (Hoefs, 2015). This change is related to anthropogenic fossil fuel burning over the last 150 years (Hoefs, 2015). This is important to know when comparing modern organisms' $\delta^{13}C$ values to those of ancient organisms as this offset must be taken into consideration and compensated for with a correction factor.

The inorganic carbon used by plants in marine environments is a mix of deep-water carbonate and oxidized organic matter (Craig, 1970). Reported $\delta^{13}C$ values of dissolved inorganic carbon from the deep ocean (below 3,000 meters) range from 0.5‰ in the South Pacific (Craig, 1970) to 0‰ in the North Pacific (Kroopnick et al., 1970). Surface ocean water appears to be more uniform, with reported modern $\delta^{13}C$ values of approximately 2.2‰ (Craig, 1970; Kroopnick et al., 1970). These values are higher than that of atmospheric CO_2, which is one reason why the $\delta^{13}C$ values of marine organisms tend to be higher than those of terrestrial organisms (Chisholm et al., 1982).

The $\delta^{13}C$ of dissolved inorganic carbon available to freshwater plants varies in response to factors including the type and amount of sediment accumulated in the water, the presence of suspended organic and inorganic matter, and water movement (Ivanić et al., 2018; Keeley & Sandquist, 1992). In one review, $\delta^{13}C$ of dissolved inorganic carbon in fresh water environments was shown to range from +1‰ to -21.2‰ and the $\delta^{13}C$ value of freshwater plants varied even more, ranging from -11‰ to -50‰ (Keeley & Sandquist, 1992). This is one factor in the high $\delta^{13}C$ variability of freshwater organisms.

6.3.1.2 Photosynthesis

Understanding the basic principles of photosynthesis is important as it is the source of carbon in plants and thus ecosystems. The three photosynthetic pathways (discussed below) result in different $\delta^{13}C$ values in plants. Carbon dioxide (CO_2), water (H_2O), and energy (photons) from the sun are transformed, via chemical reactions, to reduced carbon, carbohydrates ($(CH_2O)_n$), and oxygen (O_2). Via photosynthesis, plants remove CO_2 from the atmosphere and use it to synthesize amino acids and carbohydrates necessary for metabolic processes and growth (Bütz et al., 2014). Light energy is absorbed by the pigment chlorophyll and is used to produce high energy intermediates (ATP) and strong reductants (NADPH) in addition to producing gaseous oxygen via the oxidation of water (Björkman & Berry, 1973). ATP and NADPH then drive reactions that reduce atmospheric carbon to form carbohydrates. The isotope effect seen in plants is a result of the differing physical properties of ^{13}C and ^{12}C (O'Leary, 1988) as they are used in photosynthetic pathways.

C_3 Plants

Most plants utilize the Calvin-Benson (C_3) photosynthetic pathway in the dark reaction portion of photosynthesis. This chemical pathway produces 3-carbon phosphoglyceric acid which can be used to form other carbohydrates (Björkman & Berry, 1973). CO_2 enters the plant via the stomata on the leaves after which it diffuses to the mesophyll where it is fixed by ribulose-1,5-bisphosphate (RuP2) (Marino & McElroy, 1991). In this step, CO_2, ATP, and NADPH are transformed into PGAL (phosphoglyceraldehyde) which can be used to make carbohydrates. In the C_3 pathway, strong discrimination occurs against ^{13}C during CO_2 fixation by ribulose biphosphate carboxylase/oxygenase (rubisco) (Lee-Thorp, 2008). The isotope effect is partially due to the slower diffusion of $^{13}CO_2$ compared to the lighter $^{12}CO_2$ but primarily due to the biomechanical properties of rubisco which reacts more readily with $^{12}CO_2$ (Lambers et al., 2008; Marino & McElroy, 1991). The main steps between CO_2 diffusion into intercellular space and rubisco that cause fractionation are diffusion and carboxylation (Lambers et al., 2008). This results in the plant being depleted in ^{13}C relative to ^{12}C and expressing a lower $\delta^{13}C$ value with a range of -24‰ to -36‰ and an average value of -26.5‰ (Hare et al., 1991). C_3 plants include trees, shrubs, and most human foods.

C_4 Plants

The C_4 pathway is a recent evolutionary adaptation to hot, arid climates and has evolved multiple times in a variety of plant taxa (Ehleringer et al., 1997). C_4 plants include grasses such as sorghum, millet, maize, and many wild grasses. C_4 plants differ from C_3 plants anatomically as well as physiologically. Anatomically, they have a sheath of thick walled cells surrounding the vascular bundle referred to as Kranz anatomy (Lambers et al., 2008). Similar to the C_3 cycle, the Hatch-Slack pathway begins with the diffusion of CO_2 into the cell via the stomata. The CO_2 then dissolves into the cell sap and is converted to a bicarbonate (HCO_3^-) (Marino & McElroy, 1991). The CO_2 or HCO_3^- is released in bundle sheath cells and is fixed by RuP2. The Hatch-Slack (C_4) pathway differs from the C_3 pathway in its net discrimination against ^{13}C, as it concentrates CO_2 in bundle-sheath cells prior to the rubisco cycle with the result that little of the ^{13}C that is discriminated against in the rubisco cycle is diffused back to the atmosphere (Lambers et al., 2008). Furthermore, mesophyll cells contain phosphoenolpyruvate carboxylase which scavenges most of the CO_2 that would otherwise be lost (Lambers et al., 2008). This is beneficial in hot and arid environments as C_4 plants are more efficient at CO_2 incorporation and, as a result, require their stomata to be open for less time reducing water loss. Thus, fractionation does not occur in this stage of the process and instead is mainly caused by diffusion (Lambers et al., 2008; Lee-Thorp, 2008). This results in high $\delta^{13}C$ values relative to C_3 plants, with a range of -9‰ to -16‰ and an average C_4 plant value of -12.5‰ (Hare et al., 1991).

Crassulacean Acid Metabolism Plants

Crassulacean acid metabolism (CAM) plants are mainly arid-habitat succulents such as cacti, euphorbias, agaves, and bromeliads including prickly pear and pineapples. CAM plants can use both C_3 and C_4 photosynthetic pathways. As a result, CAM plants' $\delta^{13}C$ values can span the ranges typical of C_3 and C_4 plants depending on environmental conditions (O'Leary, 1981; Troughton et al., 1974). Given their usual arid environments, though, their stomata are often closed for most of the day; this means that ^{13}C cannot readily diffuse out of their leaves, with the result that their $\delta^{13}C$ values are usually more C_4 typical (Lambers et al., 2008).

6.3.1.3 Variation Between Individuals

Although the carbon sources and photosynthetic pathways of plant groups lead to distinctive ranges of isotopic values, measurable $\delta^{13}C$ differences can occur between plants using the same pathway and drawing from the same carbon source. These differences have two main origins: environmental variation and genetic differences between strains (Björkman & Berry, 1973; Buchmann et al., 1996; Tieszen, 1991).

Environmental parameters can stem from factors that affect the function of the stomata or the enzymatic conductance of the plant (Tieszen, 1991). These include irradiance, water stress, soil/water nutrient level, temperature, salinity, and atmospheric CO_2 concentration (Drucker et al., 2008; Tieszen, 1991). These factors may be synergistic or antagonistic, resulting in complex $\delta^{13}C$ variation (see Edwards and colleagues 2000). Only two examples - the canopy effect and the impact of water supply - will be discussed here.

The canopy effect is a pattern of $\delta^{13}C$ variation typical of plants in dense forests. When mixing between local air and the wider atmosphere is restricted (such as in closed tree canopies or greenhouses), the ambient CO_2 in a locale can become ^{13}C-depleted (Tieszen, 1991). In a closed canopy environment, vertical gradients are observed in both concentration and $\delta^{13}C$ of CO_2, with higher CO_2 concentration and $\delta^{13}C$ values seen near the top of the canopy than at the forest floor (Drucker et al., 2008).

Water stress on a plant results in stomatal closure to prevent excessive water loss (Johnson et al., 1989; Lambers et al., 2008; Tieszen, 1991). If light energy is present during the water stress this can result in reduced discrimination against ^{13}C, elevating the plant's $\delta^{13}C$ value (Tieszen, 1991). For example, significant differences were seen in $\delta^{13}C$ values of *Vicia fabia* plants when treated, in a laboratory setting, with different levels of irrigation; the plants with lower irrigation showed increased $\delta^{13}C$ values by roughly 1‰ over those that were irrigated (Edwards et al., 2000).

6.3.1.4 Variation Within Individuals

Within an individual plant, tissue $\delta^{13}C$ values can vary based on the pathways of biosynthesis of the tissue type involved. This has been shown for instance by Tieszen and Fagre (1993), who found different factors of maize seeds (lipids, proteins, and so on) to have different isotopic values. These differences can cause $\delta^{13}C$ variation between anatomical structures such as leaves versus seeds or stems of plants. Variation can also be seen within a single part of the plant. For example, stomata do not respond homogeneously across a single leaf, resulting in very small differences within a single leaf (Lambers et al., 2008).

6.3.2 Carbon in Heterotrophs

Heterotrophs cannot produce their own energy and instead consume other organisms. When consumed, the isotopic signal of the food source is transferred to the consumer. This means that the consumer will reflect the $\delta^{13}C$ values of items in the diet. Overall, the body is reflective of digestible carbon in the diet with a small fractionation offset of approximately +1‰ (DeNiro & Epstein, 1978). Once items in the diet are digested, the pathways their carbon atoms take to become part of the consumer's body differ based on the particular tissue into which the carbon is being incorporated (France & Owsley, 2015). These differences result in varying tissue $\delta^{13}C$ values within an individual. Variation can be seen between individual amino acids and fatty acids, between lipids and proteins, between different tissues, and within the same tissue due to variable turnover rates and the body's ability to synthesize the tissue from different dietary components (Lee-Thorp et al., 1989). The enrichment of an herbivore's bone collagen $\delta^{13}C$ over the value of its diet is approximately 5‰ (Lee-Thorp et al., 1989; Sullivan & Krueger, 1981; van der Merwe & Vogel, 1978). Further detail on streaming diet to bone can be found in section 6.5. After this, a +1-2‰ fractionation offset is expected at each trophic level in both herbivores and omnivores. This phenomenon helps researchers to distinguish between marine and terrestrial species because marine trophic chains tend to be longer, with the result that high trophic level marine organisms typically have higher $\delta^{13}C$ values than high trophic level terrestrial organisms (Halley & Rosvold, 2014).

6.3.2.1 Variation between Tissues

Based on the specific tissue that is being synthesized, differences in carbon incorporation can cause δ^{13}C differences between tissues. For example, lipids have a lower δ^{13}C value than other tissues due to fractionation during the oxidation of pyruvate to acetyl CoA, the main source of carbon in lipid biosynthesis (DeNiro & Epstein, 1977). Bone will be discussed in further detail in section 6.5.

6.3.2.2 Tissue Turnover

A final source of δ^{13}C variation within an individual is the varying turnover rates of different tissues. Since the isotopic composition of tissues is directly related to that of the diet, any significant dietary δ^{13}C change over an organism's lifetime should eventually lead to δ^{13}C shift in the tissues of the body. This, however, does not occur all at once; tissues incorporate new isotopes during normal repair, growth, and remodeling, which occur at different rates between tissues. Turnover differences are also seen within some tissue types (Hedges et al., 2007). Specifically in the skeleton, elements with thin cortices and abundant cancellous bone such as the ribs have a much faster turnover rate than thick cortical bone such as that of a femoral shaft (Hedges et al., 2007). Thus, if the diet changed, the new isotopic composition would be reflected in the ribs prior to the femoral shafts, resulting in δ^{13}C variations within the skeleton of a single individual. Variation in tissue turnover are also seen with age: skeletal tissues of juveniles that are still growing will turn over faster than those of adults (where turnover mainly stems from repair and maintenance) with infants displaying the fastest turnover rates (Scheuer & Black, 2004). Unlike bone, teeth do not remodel throughout life (Scheuer & Black, 2004). This means that teeth retain the isotopic signature from when they were formed (as juveniles) throughout life.

6.3.2.3 Differentiating Dietary Types

Differences in the $\delta^{13}C$ values of plants using different photosynthetic pathways as well as differences in plants from varying environments allows diets based on broad classes of plants to be distinguished in dietary reconstructions. As previously mentioned, C_3 plants have an average $\delta^{13}C$ value of -26.5‰ whereas C_4 plants have an average $\delta^{13}C$ value of -12.5‰. These differences are translated to herbivores and subsequently to predators consuming herbivores with a fractionation offset. Marine resources, due to their use of dissolved carbonate as a carbon source and to longer trophic chains, typically have higher $\delta^{13}C$ values than those from terrestrial environments (Katzenberg, 2008; Lee-Thorp, 2008). Freshwater organisms' $\delta^{13}C$ values are more variable due to irregularity of the initial carbon source; in many bodies of water, though, they display low $\delta^{13}C$ values when compared to terrestrial and marine species (Katzenberg, 2008). General patterns are cited here rather than value ranges because the exact values of groups of organisms are specific to a given region.

6.4 Nitrogen

The nitrogen isotopic system distinguishes between organisms of differing trophic levels as well as marine and freshwater versus terrestrial ecosystems. ^{14}N accounts for 99.6% of atmospheric nitrogen whereas ^{15}N makes up less than 0.4% (Roberts et al., 2005). The proportion of ^{15}N to ^{14}N ($\delta^{15}N$) is compared to the universal standard AIR (ambient inhalable reservoir). The initial incorporation of nitrogen into the food chain is more complex than that of carbon and involves the type of nitrogen obtained by a plant, the manner in which it is obtained, the plant part, and the climate (Szpak, 2014).

6.4.1 Nitrogen in Ecosystems

The nitrogen cycle is complex with multiple feedbacks, interactions, and transformations (Craine et al., 2015; Wada et al., 1975). Nitrogen exists in the atmosphere as N_2 (N=N). Within the atmosphere there is, generally, no variation in the $\delta^{15}N$ value (Mariotti, 1983). Most bulk soils are slightly enriched in ^{15}N over the atmosphere (Kohl et al., 1971; Mariotti et al., 1982; Shearer et al., 1978), with $\delta^{15}N$ values that fall into the 2‰ - 6‰ range (Hobbie & Högberg, 2012). Soil studies by Hobbie and Högberg (2012), as well as by Mariotti and colleagues (1980) suggest that $\delta^{15}N$ values increase with soil depth.

N_2 cannot be used directly by most plants or animals due to the double bond between its two nitrogen atoms. To be utilized by plants, the double bond must be cleaved, a reaction performed naturally by a class of bacteria called diazotrophs. Nitrogenase, the enzyme that fixes (cleaves) the nitrogen, is comprised of metalloproteins and is damaged by oxygen (Postgate et al., 1982). There are two types of diazotrophs: those that are free-living in soil or water and those with symbiotic relationships with legumes. Both types cleave N_2 and incorporate its nitrogen into nitrates and nitrites; however, plants with symbiotic relationships can use the fixed nitrogen directly whereas free-living diazotrophs release the nitrogen into the soil or water. Other sources of soil nitrogen include animal waste, detritus, and decomposing fauna, all of which impact the overall natural abundance of usable nitrogen in the soil as well as its $\delta^{15}N$ value (Szpak, 2014). The $\delta^{15}N$ value of the total soil may not be representative of what gets taken up by a plant (Shearer & Kohl, 1989) due to variations in the bioavailability of different soil nitrogen compounds. Similarly, nitrogen cannot be assumed to be homogenously distributed within the soil and different components of the soil will have different usable nitrogen levels (Mariotti et al., 1982; Tiessen et al., 1984). All of this helps to create a certain amount of $\delta^{15}N$ variation in the plants that grow in a given locale.

6.4.2 Nitrogen in Autotrophs

The environmental distribution of nitrogen discussed above influences but does not completely determine the $\delta^{15}N$ values of autotrophs. The source of fixed nitrogen used by a plant will impact its tissue $\delta^{15}N$ value (van Groenigen et al., 2015).

An important aspect of this patterning is that leguminous plants consistently have lower $\delta^{15}N$ values than non-legumes (Szpak et al., 2014). This is due to the source of the nitrogen used by the plant: legumes derive a portion of their nitrogen from atmospheric N_2 which has $\delta^{15}N$ values around 0‰ (Mariotti, 1983; Yoneyama et al., 1986). Since there is little fractionation during N_2 fixation, legumes typically have a $\delta^{15}N$ of around 0‰ (Kohl & Shearer, 1980).

Non-leguminous plants obtain their nitrogen from the soil. Thus, the $\delta^{15}N$ will be reflective of the soil the plant grew in with a fractionation offset from the uptake of soil nitrogen into plant tissue, which varies based on the plant and the concentration of nitrogen at the root (Craine et al., 2015). One cause of the $\delta^{15}N$ variation seen in non-leguminous plants is that most depend on symbiotic relationships with mycorrhizal fungi for some portion of their nitrogen (Mariotti et al., 1980). Mycorrhizal fungi have a mutualistic relationship with plant roots providing nitrogen and phosphorus (along with other nutrients) in exchange for photosynthates (Szpak, 2014). The fungi function at the interface of the plant and soil; their hyphae have a high surface area and extensive enzymatic activity (Craine et al., 2015; Hobbie & Högberg, 2012).

The presence of mycorrhizal fungi will impact the $\delta^{15}N$ of the plant as the retention of ^{15}N by the fungi leads to decreased $\delta^{15}N$ in the plant.

Globally there is large variation in plant $\delta^{15}N$ values, which range over a span of 35‰; most plants stay in a more restricted range, though, with 95% of samples considered for one review falling into a narrow window between -7.8 and 8.7‰ (Craine et al., 2009). For an overview of plant $\delta^{15}N$ values in various ecosystems see Virginia and colleauges (1989).

6.4.3 Nitrogen in Heterotrophs

As with carbon, stable nitrogen isotope values of heterotrophs are fundamentally determined by the values of their diets. Final tissue values are determined by a number of factors, the most important of which are the trophic level effect, the effects of nursing and weaning, and the impact of malnutrition and stress.

6.4.3.1 The Trophic Level Effect

In heterotrophs, fractionation occurs during the excretion of nitrogenous waste, with the light isotope being preferentially excreted. The heavy isotope remains in the organism, resulting in tissues with a higher $\delta^{15}N$ value than the diet that was consumed and leading to stepwise ^{15}N enrichment with increasing trophic levels (Minagawa & Wada, 1984). This being the case, the highest $\delta^{15}N$ values should occur in animals at the highest trophic level assuming that the original nitrogen sources are equivalent (Minagawa & Wada, 1984). A stepwise fractionation offset of 3-5‰ is expected in bone collagen (Bocherens & Drucker, 2003; DeNiro & Epstein, 1981; Minagawa & Wada, 1984; Schoeninger & DeNiro, 1984). This means that, hypothetically, each level of the food chain would be elevated 3-5‰ over what the animal is consuming. Due to the greater complexity of their food webs, marine resources have significantly higher $\delta^{15}N$ values than terrestrial ecosystems (Minagawa & Wada, 1984). This is a result of the longer trophic level chains typical of these environments. Stepwise $\delta^{15}N$ elevation works similarly in freshwater ecosystems as it does in marine ecosystems also resulting in high $\delta^{15}N$ values relative to land organisms (Katzenberg & Weber, 1999).

It is important to recognize that trophic levels must be understood relative to the varied local $\delta^{15}N$ baselines of different environments. These are varied enough to obscure trophic level differences if the local baseline is not evaluated (Schoeninger & DeNiro, 1984). This highlights the need for studies of local typical $\delta^{15}N$ values in each study region.

6.4.3.2 Nursing and Weaning

A complication that must be considered whenever populations of mammals are studied is the impact of nursing and weaning. Weaning is the transition juvenile mammals go through when they switch from consuming milk from their mother to other foods; in some species, including humans, it has a significant impact on juvenile $\delta^{15}N$ values.

Neonate mammals are typically assumed to have similar $\delta^{15}N$ values as their mothers as nutrients are passed through the placenta with little to no fractionation offset (Beaumont et al., 2015). For many mammalian species this changes once the animal is born; because its mother's milk is synthesized from her diet and tissue stores, the nursing animal's tissues will shift to show a trophic level elevation above her tissues (Fogel et al., 1989). A cross-species study of carbon and nitrogen fractionation between mothers, neonates, and nursing offspring has shown variability in the presence and magnitude of this nursing offset, demonstrating that species specific studies are needed to confirm the fractionation expected (Jenkins et al., 2001). Most modern and archaeological studies have examined human samples (e.g. Fuller et al., 2006).

However, nursing offsets have also been shown in cows (Balasse et al.,, 2001), sheep (Makarewicz, 2014), and non-human primates (Austin et al., 2013).

There is limited evidence for isotopic nursing signals in pigs due to a general lack of research interest. Two papers, Jenkins and colleagues (2001) and Webb and colleagues (2016), have stable carbon and nitrogen isotope data for piglets and sows. The data they present indicates that there is no significant nursing elevation in pigs. This suggests that nursing will not affect the scatter of my data.

6.4.3.3 Malnutrition and Stress

Malnutrition and physiological stress can alter isotopic values of an individual. This is primarily studied through the nitrogen balance in the body being impacted by diet and deviations in nitrogen homeostasis (Fuller et al., 2005; Katzenberg & Lovell, 1999). In periods of fasting or starvation, the body begins to utilize physiological responses to survive including the catabolism of tissue and gluconeogenesis to produce energy (Bauchinger & McWilliams, 2012; Hall, 2012; Marshall Douglas McCue, 2012; Reitsema, 2013). Glycogen stores in the body can be utilized for a couple days before the stores run out (Hall, 2012). This is followed by an increase in adipose tissue lipolysis (in which glycerol is converted to glucose via gluconeogenesis) and ketone oxidization – the use of ketone bodies for energy (Hall, 2012; Marshall D. McCue, 2010). Protein catabolism follows as the last resort of the body (McCue, 2010) and this is where isotopic $\delta^{15}N$ changes are visible – this tipping point is referred to as the threshold effect (Hatch, 2012). Until the threshold point is reached during periods of starvation, no $\delta^{15}N$ increases will occur. This is why $\delta^{15}N$ changes are not observed in hibernating animals; they are utilizing fat stores for energy. When periods of starvation are of sufficient length isotopically, an enrichment of $\delta^{15}N$ values should be observed (Mekota et al., 2006). However, the changes are hypothesized to affect tissues with high protein turnover first suggesting that organs such as the small intestine will be affected much faster than bone (Bauchinger & McWilliams, 2012). Generally, however, any tissue that experiences atrophy or wasting will produce elevated $\delta^{15}N$ values (Katzenberg & Lovell, 1999).

6.5 Stable Carbon Isotopes in Skeletal Tissues

Bone collagen is the most routinely used tissue fraction for archaeological stable isotope analysis due to its abundance, resistance to diagenesis and ease of isolation (Collins et al., 2002). Other organic components of bone are potentially available for analysis; for example, osteocalcin (a non-collagenous protein) has been identified in dinosaur bones from 75 million years ago (Muyzer et al., 1992). However, it is less likely that collagen will be isotopically impacted by post-mortem environments than other organic fractions of bone (Collins et al., 2002).

Although this study only considers bone collagen (see Chapter 7), bone, enamel, and dentine mineral can also be used in stable isotope analysis. Mineral is often used in conjunction with collagen or when collagen is not preserved (Lee-Thorp & Sponheimer, 2003). Collagen and hydroxyapatite carbon sources are derived from different pathways and different parts of the diet (Krueger & Sullivan, 1984), so must be studied separately in isotopic analyses.

During the early years of archaeological stable isotope analysis two models for carbon incorporation into bone were initially proposed: scrambling (which assumed that carbon atoms from all dietary sources were mixed and used evenly to form all tissues of the consumer) and routing (which assumed that bone collagen carbon is preferentially derived from amino acid carbon and thus from dietary proteins) (Lee-Thorp, 2008). These models were tested by

Ambrose and Norr (1993), whose results suggested that while the carbon in bone mineral is drawn from carbon in the whole diet, carbon in dietary proteins will be preferentially routed to collagen. Collagen synthesis requires many amino acids that must be directly obtained from the diet (Larsen, 2015). Humans can produce 11 out of the 19 amino acids found in bone collagen; the rest (essential amino acids) must come directly from the protein of foods consumed (Müldner, 2005). Thus, foods high in carbohydrates or lipids but low in protein, such as vegetables or oils, which may be calorically important (Müldner, 2005), will be under-represented in collagen (Lee-Thorp, 2008) while animal protein is over-represented (Harrison & Katzenberg, 2003). A C_4 signature, therefore, will only be visible if protein from the plant was a major part of overall dietary protein (Harrison & Katzenberg, 2003). $\delta^{13}C$ values underestimate the isotopic composition of non-protein dietary contributions even at low protein diets, as up to 20% of the non-protein C_4 signature is invisible in collagen (Koch et al., 1997). From this perspective bone mineral can be seen as providing a more complete understanding of diet than collagen, as there is no preferential routing, thus the isotopic signature is more reflective of the overall diet. While this can make considering both collagen and carbonate useful in some circumstances (e.g. Kusaka, 2019), collagen is still typically favoured as a robust and easily isolated dietary indicator in archaeological studies (Lee-Thorp, 2008).

6.6 Chapter Summary

This chapter provides an overview of the foundations of stable isotope analysis as related to understanding pig husbandry practices. Stable isotope analysis allows researchers to examine diet throughout life. Stable isotopes vary systematically in the environment causing predictable distinctive signatures that can be related back to dietary components. Minor differences in mass of isotopes of the same element cause them to interact differently, even at equilibrium; this is the baseline cause of fractionation, the process through which lighter isotopes preferentially react and are excreted. Although used in conjunction in dietary reconstruction, stable carbon and nitrogen isotopes were discussed separately as they represent two different isotopic systems in the environment. Stable carbon isotopes are capable of differentiating diet based on photosynthetic pathways. C_3 plants (which make up most human food sources) have a $\delta^{13}C$ value lower than that of C_4 plants (includes maize, millet, and arid grasses). CAM plants can use either photosynthetic method. In heterotrophs, bone collagen is elevated by ~5‰ over the diet with a fractionation offset of ~1-2‰ each trophic level. Nitrogen is used to understand trophic level and differentiate marine and freshwater resource consumption. The nitrogen system is more complex than that of carbon. N_2 needs to be cleaved prior to being used by plants. Legumes are noted for having lower $\delta^{15}N$ values due to their ability to utilize atmospheric nitrogen. Non-leguminous plants obtain their nitrogen from the soil. Some species have a symbiotic relationship with mycorrhizal fungi. In heterotrophs, a stepwise enrichment of ~3-5‰ occurs at each trophic level; due to the long food chains of marine environments, marine resources have higher $\delta^{15}N$ values than freshwater or terrestrial resources.

7 Isotopic Applications

This chapter will provide a review of published stable carbon and nitrogen studies in Greece, methods to interpret pig husbandry practices, and isotopic studies of pig husbandry. The review of stable isotope studies in Greece will provide a general baseline of stable carbon and nitrogen values in the region as well as the interpretations made by other researchers. Reviewing different methods of interpreting stable carbon and nitrogen to understand husbandry practices will provide the basis on which I will interpret my results. Finally, a review of isotopic studies of pig husbandry will show the applicability of this method to understanding pig husbandry.

7.1 Published Results

This section will contain a literature review of stable carbon and nitrogen isotope studies in Greece from the Neolithic to the Medieval period. I have only included studies that with faunal samples, however, I will mention the interpretations of human diet when applicable.

7.1.1 Neolithic

The Neolithic, as previously reviewed in Chapter 2, was a transformative period in Greece that saw the adoption of agriculture and domesticated animals. Kontopoulos and Sampson (2015) propose a predominately C_3 terrestrial diet from Tharrounia on Euboea. This study included four ovicaprid samples all of which indicated a C_3 diet. Vaiglova and colleagues (2014) examined early agricultural practices at the site of Kouphovouno in southern Greece. They analyzed a combination of ancient crop samples (wheat, barley, pea, and lentil) and faunal material (cattle, dog, sheep, goat, pig, boar, hare, bear, and wild goat). Of the fauna, the sheep, goat, and cow samples clustered together, as did the pigs and dog. The results suggest small scale mixed farming with the potential of a manuring signal. Papathanasiou (2015) presented faunal data from a number of Neolithic sites that previously had few or no faunal samples studied. The sites include Alepotrypa, Franchthi, Theopetra, Xirolimini, Mavopigi, and Kephala. Cow, sheep/goat, deer, pig, boar, dog, fox, fish, cat, and badger were all included in the study. Overall, the fauna display $\delta^{13}C$ values indicating a C_3 terrestrial diet. The pigs from the majority of the sites display values consistent with an omnivorous diet, however, those from Alepotrypa appear to have been herbivorous. The cows sampled from Aleopootrypa had elevated $\delta^{13}C$ values, which the authors interpreted to mean the cows were grazing on or were being foddered with C_4 plants. Triantaphyllou's dissertation work (1999) included fifteen faunal samples from the Neolithic site of Markriyalos II. Red deer (n=5), pig (n=5), and wild boar (n=5) were sampled. The red deer showed $\delta^{13}C$ values consistent with a C_3 terrestrial diet and the pig and boar showed $\delta^{13}C$ values intermediate between those of the red deer and the humans. The domesticated pigs sampled had enriched $\delta^{15}N$ values that overlapped with the humans sampled, suggesting the pigs may have been consuming human waste. Vaiglova and colleagues (2018) also studied samples from Makriyalos I. Their study examined cattle husbandry through a series of isotopic studies including $\delta^{15}N$ and $\delta^{13}C$ bone collagen, incremental $\delta^{13}C$ and $\delta^{18}O$ of tooth enamel carbonate, and $^{87}Sr/^{86}Sr$ of cattle tooth enamel. The study included cattle (n=19), sheep (n=20), goat (n=19), red deer (n=3), and emmer wheat (n=5). Most of the samples had $\delta^{15}N$ values elevated over those sampled by Triantaphyllou (1999) though the researchers suggest this is likely due to interlaboratory variation. The cattle had high $\delta^{13}C$ values relative to the other domesticates sampled. The authors suggest this reflects increased C_4 plant consumption due to differences in physiology or pasturing schemes.

7.1.2 Bronze Age

The Bronze Age is interesting in Greece as it sees the establishment of two independent cultures: Minoan on Crete and Mycenaean in Central and Southern Greece. The palatal structures involved in both have received a considerable amount of attention including zooarchaeological studies. Isotopically, there are four studies that include animal samples.

Nitsch and colleagues (2017) provide a large sample of crop, faunal, and human samples from two Middle Bronze Age (MBA) to early- Late Bronze Age (LBA) sites (Archontiko and Thessaloniki Toumba). The faunal assemblage sampled includes sheep, goat, pig, boar, cattle, aurochs, roe deer, fallow deer, red deer, dog, and hare. The faunal samples from Archontiko suggest a range of feeding strategies including cattle potentially grazing in salt marshes (suggested based on their elevated stable nitrogen isotope values). The sheep and pig samples are clustered and suggest grazing on open anthropogenic agricultural landscapes. Interestingly, the goats differ, instead showing a signal more similar to the deer. The pigs and dogs at Archontiko show elevated δ^{15}N values with the dogs overlapping with some of the humans and the pigs at Thessaloniki Toumba are isotopically similar to the wild boar. In addition to the faunal samples the study also included a number of crops recovered from the sites including barley, emmer, einkorn, spelt, free-threshing wheat, lentil, bitter vetch, celtic bean, pea, millet, and flax. The authors suggest the δ^{15}N enrichment of the barley sampled may be due to manuring, specifically the preferential manuring of barley.

Triantaphyllou and colleagues (2008) sampled eight animals in their study of human diet at MBA Lerna. The fauna included sheep/goat, cow, pig, and red deer. Overall the faunal data suggests a C_3 terrestrial diet. The sheep/goat samples (n=2) display elevated δ^{15}N interpreted by the authors to suggest anthropogenic practices, potentially manuring. Conversely, the pigs sampled (n=2) had low $\delta^{15}N$ values interpreted to represent a primarily vegetarian diet – likely due to penning.

Petroutsa and colleagues (2009) included six faunal samples in their study of human diet at the LBA site of Voudeni. The fauna sampled include bird, sheep, and turtle. The bird sampled (n=1) had a $\delta^{15}N$ value suggesting the inclusion of marine resources in its diet. The sheep sampled (n=3) display values suggesting a C_3 terrestrial diet. The turtle (n=1) had a low $\delta^{13}C$ value suggesting a diet of freshwater plants.

Petroutsa and Manolis (2010) included seven faunal samples in their study of human diet from four sites from the LBA (Almyri, Zeli, Agia Triada, and Kalapodi). The fauna includes cow, cat, dog, turtle, and sheep. The sheep values suggest a C_3 terrestrial diet, while the cows display values more consistent with a predominately C_3 diet with the inclusion of C_4 plants. The two turtle samples had a freshwater plant diet. The cat and the dog samples have $\delta^{15}N$ values indicating the incorporations of animal protein in the diet. The humans generally clustered with $\delta^{15}N$ and $\delta^{13}C$ values suggestive of a C_3 terrestrial diet.

7.1.3 Iron Age

Panagiotopoulou and colleagues (2016) included six faunal samples in their study of early Iron Age diet at Halos. These included two animals identified only as herbivores, as well as sheep/goat, horse, and cattle. The results generally suggest a C_3 terrestrial diet with $\delta^{13}C$ elevation in one of the herbivores and the cow, indicating the consumption of C_4 plant resources. Papathanasiou and colleagues (2013) included ten faunal samples from the early Iron Age site of

Agios Dimitrios. The fauna included sheep/goat, cow, pig, and turtle and their values are suggestive of a C_3 terrestrial diet.

7.1.4 Classical Period and Hellenistic

Vika and colleagues (2009) examined diet at Classical Thebes. The authors suggest that the 5‰ enrichment of the humans sampled over the fauna could be due to the consumption of freshwater fish, which typically show low $\delta^{13}C$ values but high $\delta^{15}N$ values. Sparkes' dissertation work (2017) examining human diet at the Hellenistic site of New Halos in Thessaly included nine faunal samples. The results suggested a terrestrial C_3 diet. Further interpretation was withheld, however, given the small number of individuals sampled.

7.1.5 Byzantine

Garvie-Lok (2001) included 34 faunal samples from Byzantine Mytilene, Athens, and Corinth. Overall, the results suggest a terrestrial C_3 diet with possible, albeit minimal, C_4 consumption at Corinth and Athens. Bourbou and Richards (2007) included ten faunal samples in their study of human diet at Kastella. The sheep and deer displayed values consistent with an herbivorous terrestrial C_3 diet. Interestingly, the goats sampled (n=5) displayed somewhat higher $\delta^{13}C$ values which the authors interpreted to suggest the inclusion of C_4 plants or marine plants (such as seaweed) in the diet. The pigs sampled (n=3) had stable isotope values indicative of a C_3 based diet with the inclusion of higher trophic level protein.

7.2 Interpreting Carbon and Nitrogen

7.2.1 Interpreting Animal Husbandry

Animal husbandry can be examined through a variety of stable isotopic systems, including carbon and nitrogen to examine diet, but also strontium and oxygen isotopic systems which are typically used to identify season of birth (for an example of oxygen isotopes being used to examine diet, see Balasse and colleagues (2006)). Since the focus of my study is diet, I will emphasize the δ^{13}C and δ^{15}N literature.

The basis of understanding husbandry isotopically is that different diets are representative of different conditions, habitats, and behaviors. Isotopically, it is expected that there would be a few indicators suggesting that pigs were extensively managed. Primarily, the pigs would be expected to have stable carbon and nitrogen isotope values similar to sheep and goats from the same community as they would have access to the same environment and resources and thus would be consuming a similar diet which would be reflected in their isotopic signals. Importantly, pig δ^{15}N values would not be raised significantly over those of sheep and goats as both would primarily have access to an herbivorous diet. However, as pigs are omnivores and consume a varied diet, the carbon and nitrogen values are expected to be more varied than sheep and goats in similar environments. It would also be expected that the pigs would appear relatively homogeneous isotopically as, on an intra-population level, all pigs would have access to the same foods.

Conversely, it is possible that the pigs were kept at a much smaller, domestic level. In this model, pigs would have been kept primarily at the house and would have been foddered, with their diet likely containing refuse and scraps from the household. Isotopically, pigs kept at a household level would be expected to have elevated δ^{15}N values in comparison to sheep and goats as human food waste would include foods at higher trophic levels than the herbivorous sheep and goat would eat. Furthermore, the pig population may appear more heterogeneous as pigs kept in different households could have access to different foods. A difficulty associated with this specific study is that only one domestic context (Building 10) is represented. Thus, the heterogeneity expected from the entire site may not be represented in this study sample.

A number of distinct pig husbandry practices may have been employed. It is possible that pigs kept at a domestic level would also graze and scavenge, moving between fields and domestic contexts. This would be expected to create variation in carbon and nitrogen values, with pig $\delta^{15}N$ values likely elevated compared to the sheep and goats. To examine the potential for mixed management practices, especially surrounding questions of seasonality, incremental tooth sampling would be necessary such as in Balasse and colleagues (2012) and Frémondeau and colleagues (2012).

7.2.2 Literature Review of Pig Husbandry

7.2.2.1 Extensive Management

Balasse and colleagues (2013, 2017) identified extensive management of pigs in their studies of animal husbandry in Neolithic Southern Romania. A primarily herbivorous isotopic signal and potential dietary similarity to wild boars sampled was used to suggest a similar habitat to their wild counterpart. Hammond and O'Connor (2013) compared pig $\delta^{15}N$ and $\delta^{13}C$ values to herbivorous domestic animals in Medieval York, expecting to find relative $\delta^{15}N$ elevation in the pigs; however, only one of the pigs sampled showed $\delta^{15}N$ elevation, which was suggested to mean that most of the pigs were raised outside the city and were not household animals. Similarly, Millard and colleagues (2013) found the pigs from Dryslwyn Castle (Wales) to have values consistent with a herbivorous diet, suggesting extensive husbandry practices. Minagawa and colleagues (2005) also used an herbivore comparison to suggest pigs in Japan were consuming similar foods to deer and were likely extensively managed.

7.2.2.2 Intensive Management

Pig δ^{15}N values elevated over wild boars were used to suggest a penning signal by Guan and colleagues (2007). Similarly, Zavodny and colleagues (2018) suggested intensive management based on δ^{15}N and δ^{13}C elevation over the other terrestrial domesticates. Balasse and colleagues (2016) found that pigs at a Late Chalcolithic site in South Eastern Romania have high δ^{15}N values, one sample having the highest δ^{15}N of any terrestrial mammal at the site, similar to the dogs sampled and elevated over the wild boar. This was interpreted to suggest intensive management including, perhaps, foddering with freshwater fish refuse. Jones and Mulville (2018) suggest diverse household rearing of pigs with marine foddering in the Scottish North Atlantic Islands based on elevated δ^{15}N and δ^{13}C values. Halley and Rosvold (2014) also suggest foddering of pigs with marine resources in Norway based on high δ^{15}N and δ^{13}C values.

There has been a lot of scholarship from China regarding pig husbandry and diet as researchers have used isotopic analysis to identify domesticated pigs. Because early northern Chinese agriculture relied on millet, which is a C_4 plant, foddered pigs show a distinctive δ^{13}C signature as well as δ^{15}N elevation, and researchers can identify pigs that were being foddered. Guan and colleagues (2007) looked to distinguish wild boars from pigs based on their dietary differences. Although there was overlap in δ^{13}C values between the known pigs, known boars, and unknown suids, their δ^{15}N values differed, allowing a distinction between wild boars and foddered domesticated pigs. Cucchi and colleagures (2016) suggest a transition from a more extensive management including millet foddering to household management from the Neolithic to the Han Dynasty based on the consistently elevated $\delta^{13}C$ (suggesting millet foddering) and an increase of $\delta^{15}N$ values over time. Hu and colleagues (2009) identified three isotopic clusters of suids from the Shandong province. The low $\delta^{15}N$ and $\delta^{13}C$ values of the first group were used to suggest that the suids were boars whereas the groups with high $\delta^{13}C$ values and those with low $\delta^{13}C$ and high $\delta^{15}N$ were suggested to be pigs.

7.2.2.3 *Mixed Intensive and Extensive*

A number of studies have suggested mixed management strategies. Madgwick and colleagues (2012) suggest a change in management practices from the Late Bronze Age to the Iron Age. They suggest a transition from woodland foddering to household management based on increasing $\delta^{15}N$ values. They suggest household management based on the heterogeneity of the pig samples, which they interpret to reflect individual practices on a house by house basis. Hamilton and Thomas (2012) also suggest a transition from extensive to intensive management over time. Their interpretation, however, is unique as it is based on diachronic changes in isotopic variability rather than $\delta^{15}N$ and $\delta^{13}C$ increase or decrease. A decrease in dietary diversity, based on restricted $\delta^{15}N$ values in the second phase studied, is suggested to reflect a penning signal as the pigs would not have access to a wide variety of resources. They further suggest that the decrease in average $\delta^{15}N$ values in the second phase is the result of foddering with legumes. Guiry and colleagues (2018) examined pig diet from remains in a shipwreck from a French colony in the modern-day United States. Historical records indicate that pigs at the colony were foddered with hunted bison meat. The authors found two isotopic clusters of pigs: one with high $\delta^{15}N$ and $\delta^{13}C$ suggesting a meat-heavy C_4 diet consistent with bison foddering and the second with low $\delta^{15}N$ and $\delta^{13}C$ values suggested to be provisioned pork from France.

7.3 Chapter Summary

This chapter provides an overview of of faunal stable isotope studies in Greece and isotopic studies of pig husbandry. Although there are few Greek studies that focus primarily on faunal isotopes, a number of studies include fauna in their analyses of human diet. A review of this literature provides an overview of diets suggested for domesticates in Greece based on isotopic data. Care should be taken, though, in inferring animal diets from studies that included limited fauna and were primarily focused on human diet. This chapter also considered the interpretation of pig husbandry practices from stable isotope data. This had been undertaken by a number of researchers working in different parts of the world. Most of the studies approached this problem by comparing the pigs to other fauna, primarily herbivores or wild boars. Intensive management was suggested when the $\delta^{15}N$ values of the pigs sampled were significantly higher than the herbivores or comparable to carnivores (like dogs). Extensive management is indicated by $\delta^{15}N$ values consistent with herbivory. Some studies suggest that different strategies were employed over time correlating with other social, political, or ecological changes.

8 Materials and Methods

This chapter provides an overview of sample selection (including what criteria were used and which samples were selected), bone diagenesis, methods available for collagen isolation, the collagen isolation method used in this study, and diagenetic indicators.

8.1 Sample Selection

Samples were retrieved in July 2018 from the faunal assemblage housed in the storage facilities in Narthaki Greece. Permission for the transport of the samples to Canada was provided by both the Greek Ephorate and the Canadian Food Inspection Agency (CFIA). All of the material had previously been examined by Dr. Michael MacKinnon, the zooarchaeologist studying the Kastro Kallithea remains.

In June 2017, the potential study samples were pulled from storage by student researchers who had access to Dr. MacKinnon's inventories, but who did not have experience with pig remains. During the course of the 2018 study season, I reviewed the material pulled by the student researchers in conjunction with Dr. MacKinnon's inventory and reidentified all pig remains from the assemblage. Subsequently, I compared specific samples to a spreadsheet of the secure contexts, provided by Dr. Haagsma, to determine which pig remains were recovered from secure contexts. For samples excavated from lower layers (and thus more likely to be secure), but not listed as secure, I consulted with Dr. Haagsma to determine if the context could be considered secure. Samples from secure contexts were examined for potential signs of diagenesis, to see if their collagen was likely to be sufficiently preserved for stable isotope analysis. Criteria included overall appearance, texture, color, and condition (burnt, weathered) of the bone. Samples were also controlled for context to decrease the likelihood of sampling the same animal multiple times. Samples were considered to be from different individuals if the remains clearly represented animals of different sizes or ages, were duplicated elements (e.g. two right scapulae), or were from separate contexts. The use of different contexts does not ensure that the samples were not from the same animal (a single animal could have been deposited in multiple contexts), but based on the faunal assemblage available, assuming different animals based on context provided a useful means of identifying likely different individuals and increasing the potential sample.

Thirty pig samples were selected. These samples are primarily from Building 10 (samples MKK01-MKK28) with two samples from Acropolis Building 1 (MKK29-MKK30). A list of the pig samples, including the context, elements, and notes, is provided in Table 7.1. Ages were estimated based on Bull and Payne (1982) and cross referenced with Dr. MacKinnon's notes on age from his analysis. Samples were grouped into categories of fetal/neonate, juvenile, and adult.

In addition to the 30 pig samples, six sheep and goat bone samples were also analyzed. These samples were taken from sheep and goat mandibles collected for Katherine Bishop's dissertation research, an examination of herding practices at Kastro Kallithea using sequential enamel analysis. This small sample set is used as a comparative to the pigs, as sheep and goat are herbivores (this is discussed further in section 7.6.1). Sheep and goat mandibles were preferentially sampled if the individual's tooth was also being used in Bishop's enamel study, as this extends our knowledge of the individuals' life histories which is useful to the overall project. I also tried to include sheep and goat samples that came from similar contexts to the pig samples.

Table 7.1. Pig Samples Analyzed

Lab Number	*Context*	*Element*	*Age*[1]
MKK01	Building 10 UA2 L3S2	Mandible	Adult
MKK02	Building 10 UA3 Sondage along foundation wall	Mandible	Juvenile
MKK003	Building 10 UC2 Feature beta	Phalanx 2	Juvenile
MKK004	Building 10 UC2 F gamma L1S1	Temporal	Adult
MKK005	Building 10 UC1 annex L5S1	Metacarpal 5	Juvenile
MKK006	Building 10 C Baulk, L4S1	Left Humerus	Juvenile
MKK007	Building 10 UC1 L4S1	Metatarsal 3	Adult
MKK008	Building 10 UC2 L4S1	Metacarpal 5	Adult
MKK009	Building 10 UD2 L3S2	Scapula	Neonate
MKK010	Building 10 UE2 L3S2	Mandible from Deciduous Canine to 4th Premolar	Adult
MKK011	Building 10 UE2 L3S1	Radius	Adult
MKK012	Building 10 UF4, L3S1	Left Ulna	Adult
MKK013	Building 10 G2, Feature α, L1S1	Left Humerus	Neonate
MKK014	Building 10 G2, Feature α, L1S1	Right Maxilla	Adult
MKK015	Building 10 UH2 L2S1	Phalanx 1	Juvenile
MKK016	Building 10 H1, L2S1	Right Scapula	Juvenile
MKK017	Building 10 H2, L2S2	Left Metatarsal 3	Adult
MKK018	Building 10 UI1B L4S1	Phalanx 1	Adult
MKK019	Building 10 J2, L3S2	Right Mandible	Adult
MKK020	Building 10 J2, L3S2	Right Metacarpal 2	Adult
MKK021	Building 10 UK, Feature α	Right Metacarpal 3	Adult
MKK022	Building 10 K2, L3S1	Right Metacarpal 2	Adult
MKK023	Building 10 K2, L3S1	Right Metatarsal 4	Adult
MKK024	Building 10 K1 L2S5	Metacarpal 4	Adult
MKK025	Building 10 UL2, L2S4	Calcaneus	Adult
MKK026	Building 10 Room 4-1 L4S3	Metatarsal 3	Juvenile
MKK027	Building 10 Room 4/1 L4S3	Metapodial 3 or 4	Adult
MKK028	Building 10 Room 4/2 L2S8	Left Calcaneus	Adult
MKK29	Acropolis Building 1 U1 L4S3	Calcaneus	Adult
MKK30	Acropolis Building 1 U1 L4S3	Phalanx 2	Adult

1. Due to fragmentation, age estimates were not possible for some samples.

Table 7.2. Sheep and Goat Samples Analyzed.

Lab Number	*Context*	*Element*	*Species*
MKK31	Building 10 K2 Feature α	Mandible	Goat
MKK32	Building 10 K2 Feature α	Mandible	Sheep
MKK33	Building 10 UE3 L2S3	Mandible	Sheep
MKK34	Building 10 UI2 L2S2	Mandible	Sheep
MKK35	Building 10 UB2 L3S1	Mandible	Sheep/Goat
MKK36	Building 10 UK1 L3S1	Mandible	Sheep

8.2 Diagenesis in Bone

An essential component of effective sample choice and preparation is identifying diagenetic changes to the bone. Diagenesis broadly refers to any changes to bone composition that occur post-mortem from either intrinsic or extrinsic factors (Burton, 2008; Müldner, 2005). There is the potential for diagenetic changes to affect the isotopic composition of the bone. Due to the implications of such diagenetic alterations for the accuracy of bioarchaeological analyses, there has been extensive research into the assessment and identification of diagenesis as well as into methods for removal of contaminants (Burton, 2008). The following section will review bone structure, the general processes of diagenesis, and changes to the bone (including histological and collagen degradation) with respect to isotopic analyses.

8.2.1 Bone Composition

To understand the deterioration of buried bone, it is important to consider bone composition and structure. Bone is a composite material whose matrix is composed of both mineral and organic phases. The organic matrix of the bone is primarily a fibrous protein (Type 1 collagen). Its inorganic matrix is composed of calcium phosphate crystals (largely in the form of hydroxyapatite) deposited in and around the collagen fibrils (Currey, 2002; Katzenberg, 2008; Marks & Odgren, 2002). In addition to this structural matrix, living bone tissue also contains small amounts of water, non-collagenous proteins, polysaccharides, living cells, nerve fibers and blood vessels (Currey, 2002).

The two most abundant types of proteins in bone are Type I collagen and osteocalcin; other proteins are present but comprise an insignificant portion of the bone (reviewed in Collins et al., 2002). By weight, collagen makes up 30% of bone mass (Collins et al., 2002) and osteocalcin makes up 1-2% (P. Price, 1983). Collagen from different tissues has different amino acid compositions. Collagen of the skin, tendons, dentine, and bone is classified as Type 1 collagen (Currey, 2002). Type 1 collagen makes up approximately 95% of the organic matrix of bone, with the other 5% composed of osteocalcin, proteoglycans, and other non-collagenous proteins (Marks & Odgren, 2002). Type 1 collagen is a fibrillar collagen formed from the protein molecule tropocollagen which aggregates to form collagen microfibrils (Currey, 2002). The microfibril chains are held together by hydrogen bonds in a left-handed triple helix (Currey, 2002; Rossert & Crombrugghe, 2002). This structure gives Type 1 collagen tensile strength and makes it more resistant than other proteins in the burial environment.

8.2.2 Diagenetic Processes

As previously noted, diagenesis refers to the changes that occur in bone components such as collagen post-mortem. This differs from contamination, the presence of exogenous contaminants (van Klinken, 1999). Contamination can, however, lead to diagenetic alteration of bone. This section will review the pathways and processes that often lead to degradation in buried bone.

To be able to regulate blood levels of various elements during life, bone must be highly reactive and porous (Burton, 2008). Both of these traits endure in death, promoting chemical reactions in the post-mortem environment and inclusions of exogenous elements into the bone

(Burton, 2008). Collins and colleagues (2002) outline three ways diagenesis may occur: chemical deterioration of the organic material, chemical deterioration of the mineral component, and (micro)biological attack on the composite.

8.2.2.1 Collagen Degradation

The degradation of collagen has been extensively studied due to this molecule's use in stable isotope, radiocarbon and amino acid racemization studies (Lee-Thorp, 2008). Generally, collagen denatures when the hydrogen bonds are broken causing the fibrils to dissociate (Lee-Thorp, 2008). Rapid collagen hydrolysis requires the presence of enzymes (collagenases), but collagen hydrolysis can also be catalyzed in unmineralized collagen by hydroxyl and hydrogen ions (Collins et al., 1995; Trueman & Martill, 2002). Collagen degradation is dependent on a number of factors including time, temperature, environmental pH, microbial attack, and moisture (Collins et al., 2002; Lee-Thorp, 2008). Although these factors can all be considered separately, they are all intimately related, interacting with each other and the bone (Hedges, 2002).

Although time is a factor in preservation, it has been suggested that it is not as strongly correlated with collagen preservation as some of the other factors discussed below (Hedges, 2002). Collagen is a robust molecule and can survive tens of thousands of years in the right environments (Bocherens et al., 2005).

A major cause of collagen loss in buried bone is microbial attack (Hedges, 2002) which most frequently occurs at a neutral pH (a condition that is otherwise beneficial in bone preservation) (Collins et al., 2002). Inhibitors of microbial attack include abnormally low temperatures, very dry environments, and very wet environments (Hedges, 2002). Interestingly, one survey across multiple sites found that bacterial attack preferentially impacted human bone as opposed to faunal bone (74% of samples and 34% of samples respectively) whereas fungal attack was more common in animal bone (Jans et al., 2004). These findings suggest that the differences seen in diagenetic pathways were linked to the different burial environments animals and humans tend to be found in (middens vs. mortuary contexts) as well as differences in processing of the dead (Jans et al., 2004). The processing of the dead is an important difference; while many mortuary traditions involve intact burial, animals are often processed using methods including butchering and cooking, both of which may alter bacterial invasion of the bone. In life, the normal bacterial flora of the body are kept in their proper location and prevented from causing tissue damage and degradation by a number of checks including bacteriophages the body produces (Trueman & Martill, 2002). In death, however, these bacteria are no longer kept in check and can invade the rest of the body via the vascular system, resulting in putrefaction (Jans et al., 2004; Trueman & Martill, 2002).

8.2.2.2 Contamination

Contamination refers to the presence of exogenous substances that become part of the bone. Preservation cannot always be visually assessed for indicators of contamination as the inorganic portion of bone can be altered at the molecular level. Exogenous elements may be adsorbed onto the bone surface or they may migrate into the bone (Lambert et al., 1989). It is also possible for elements to replace structural ions of the bone mineral via substitution (Lambert et al., 1989). As reviewed by Stodder (2018) the presence of ground water is imperative in the dissolution of bone mineral. Ground water acts as the medium for ion exchange to occur, which ends when equilibrium with the depositional environment occurs. Contamination can also stem from gross contaminants such as rootlets and fungal hyphae, both of which can etch the bone and cause structural damage and may also distort the bone's stable isotope values if not removed during sample preparation. Contamination of bone can also lead to bone diagenesis as it may cause structural changes that can impact the quality of the remaining bone collagen or mineral and its suitability for isotopic analysis.

8.3 Preparing Collagen and Removing Contaminants

8.3.1 Methods Available

A number of methods have been developed for the isolation of bone collagen. Three main methods (or variations of these methods) are, however, typically used: Longin, Cape Town, and Tuross. Each method has advantages and disadvantages; thus, it is important to ensure that the collagen isolation method chosen reflects the nature of the material being analyzed as well as the questions being asked (Sealy et al., 2014).

8.3.1.1 Longin Method

The first method used to isolate collagen from archaeological bones for stable isotope analysis was the Longin method (Longin, 1971), initially developed for radiocarbon work, and its subsequent modifications by Schoeninger and DeNiro (1984) and Brown et al. (1988). The original method uses a powdered bone sample which is demineralized in an 8% hydrochloric acid (HCl) bath for a short interval of time. Hydrolysis then occurs in a weakly acidic (pH=3) hot water bath which denatures the collagen (gelatinization). Impurities are removed via centrifugation.

A modification of the Longin method reduces the degradation of protein in the isolated collagen and increases product yield (Brown et al., 1988). Brown and colleagues (1988) also added an ultrafiltration step prior to lyophilization as larger peptides (more likely to represent intact collagen) are extracted, leaving behind contaminants of lower molecular weight. A modified Longin method, sometimes with the addition of a NaOH soak (see below), has been used in many stable isotope studies (e.g. Alexander et al., 2019; Nehlich et al., 2010; Pickard et al., 2017; Rutgers et al., 2009). The modern version of the Longin method is referred to as the Oxford method by Sealy and colleagues (2014). A brief review of this method can be found in section 7.4.1.1.

8.3.1.2 Cape Town Method

Sealy (1986) developed an alternative method that starts with chunks of bone rather than bone powder. These bone chunks are demineralized by soaking for a few days or weeks in a more dilute HCl solution than that used in the Longin method. This forms a pseudomorph (collagenous form of the bone chunk from which the mineral has been removed) which is then soaked in dilute sodium hydroxide (NaOH) to remove soil contaminants (see following section). This method is simple, robust, and inexpensive and has been used in many studies (e.g. Burt, 2013; Losey et al., 2013; Taylor, 2018; Zhou et al., 2017).

8.3.1.3 Tuross Method

An alternative isolation method developed by Tuross and colleagues (1988) also uses chunks of bone. This method, however, isolates the collagen from the bone chunk by soaking the sample in ethylenediaminetetraacetic acid (EDTA) rather than a HCl solution. This method is not in as frequent use as methods using HCl for demineralization (see however, Salamon et al., 2008;

Tuross, Warinner, Kirsanow, & Kester, 2008; Warinner & Tuross, 2010). It has been shown to produce better collagen yields in poorly preserved samples (Tuross et al., 1988).

8.3.2 Researching Collagen Isolation Method Efficacy

There have been a number of studies examining the various steps involved in collagen isolation and comparing the efficacy of the different methods. Some of these are discussed here to provide context for the choice of collagen extraction method used in this study.

As previously noted, extraneous material may adsorb onto the surface of the bone. Abrasive cleaning techniques remove contamination from the outer surface of the bone introduced, post-mortem, in the burial environment (Burton, 2008; Lambert et al., 1989). Physical abrasion of the outside of the bone, however, will not remove internal contamination of the bone (Lambert et al., 1989).

Radiocarbon studies show that archaeological collagen samples untreated with NaOH may have significant contamination from humic acids and lipids (Gurfinkel, 1987). Multiple studies have analyzed the impact of NaOH treatment as a decontaminant. Three of these studies (Katzenberg, 1989; Kennedy, 1988; Lynott et al., 1986) show that some collagen is lost in the NaOH treatment. Kennedy (1988) and Lynott and colleagues (1986) suggest that, although collagen is lost, the amino acid profile of the remaining collagen is unchanged. Katzenberg (1989), however, suggests that amino acid composition might be changed if the treatment is applied for too long. As noted by Ambrose (1990), these changes, although not insignificant, are offset by the removal of humic acids and lipids that could drastically affect the isotopic composition of the sample.

Sealy and colleagues (2014) compared the Cape Town method of collagen isolation to the version of the modified Longin method used at the Max Planck Institute to prepare samples for radiocarbon dating. They determined that, for most well-preserved samples, the Cape Town method is appropriate.

8.3.3 Method Used in this Study

I used the Cape Town method with a few modifications for my samples. Due to the generally excellent preservation of the samples, it was determined that a chunk method would be appropriate. The method used followed Sealy et al. (2014) with two modifications: addition of a gelatinization step followed by a centrifugation step to remove impurities from the hydrolyzed sample. These two procedures have a long record of utility for homogenizing and purifying collagen samples after demineralization (Longin 1971). Recent studies done in the University of Alberta Department of Anthropology's sample preparation laboratory (Garvie-Lok et al., 2019; Torres Peña, 2018) have added them to the Cape Town method. This has had the positive effects of improving sample C/N, wt%C and wt%N (likely by removing acid-insoluble contaminants) and making the prepared collagen easier to weigh precisely during packing for mass spectrometry (S. Garvie-Lok, pers. comm. 2019).

The bone chunks were cut using a Dremel motor saw with a diamond cutting wheel to an approximate size of 0.5g. The external surfaces of the chunks were then cleaned via mechanical abrasion using a Dremel motor saw with a grinding attachment and sonicated at 15-minute intervals in changes of distilled water, until the water the sample was in remained clear throughout the wash (typically 1-2 washes). The samples were air-dried for a minimum of 48 hours, then weighed a minimum of two times over the span of two days to determine the starting sample weight. Multiple measurements were taken to ensure accuracy of the scale. If the measurements were divergent, a third measurement was taken. After being weighed, the samples were placed in glass jars for processing. The samples were soaked in approximately 80ml of 1% HCl at room temperature to demineralize the bone. The HCl solution was changed regularly (every 2-3 days). Prior to each change, any changes in the color of the solution were recorded, as were the texture, translucency and color of the bone and the presence of bubbles on the sample surface. Indicators that the samples were completely demineralized included lack of bubbles (indicating that the reaction was complete) and softening and translucency of the sample (indicating that its mineral content was removed). Once the sample appeared completely demineralized, the HCl solution was changed once more to ensure complete demineralization. The resulting collagen pseudomorphs were then rinsed three times with distilled water and were soaked in double-distilled water. The double distilled water was left for a minimum of 24h and then changed regularly. The pseudomorphs were then drained and soaked in 0.125M NaOH for 20 hours. Before removal from the NaOH solution, I recorded any changes in the color of the solution and the texture of the samples. The samples were then rinsed three times with purified water and soaked in distilled water for 48 hours. After this, each pseudomorph was placed in a disposable centrifuge tube to which 10 ml of double distilled water adjusted to pH 3 with a few drops of HCl was added. The sealed tubes were placed in a water bath for 48 hours at 80°C to hydrolyze the samples. Following this the tubes were removed from the hot water bath and centrifuged to separate the supernatant (hydrolyzed collagen) from the pellet (contaminants). The supernatant was removed using a disposable pipet, transferred to scintillation vials, frozen and then freeze-dried for 48 hours. Purified samples were weighed to determine collagen yield (see section 7.5.2) and were then ready for mass spectrometry.

8.4 Diagenetic Indicators

Collagen isolation that uses an acid to demineralize the bone and NaOH to remove soil contaminants is advantageous in that it is effective and inexpensive (Ambrose., 1990). The residue produced, often assumed to be pure collagen, is primarily collagen but also contains non-collagenous bone proteins and other extraneous matter (Ambrose, 1990). For the purposes of dietary reconstruction, however, the assumption that isolated residue is collagen is acceptable as long as the sample satisfies some basic quality assessment measures.

A number of standard quality assessment measures are used to determine sample quality. These include carbon and nitrogen content by weight (wt%C and wt%N), atomic C/N ratio, and collagen yield. These indicators compare the samples to modern fresh bone values, as unaltered collagen is ideally expected to be similar to that of fresh bone. These measures are used in conjunction as none alone is enough to ensure a well-preserved sample. Samples were compared to the indicator cut-off values described below. Samples that produced one or more borderline values were carefully considered in terms of their other indicator values before being passed.

8.4.1 Collagen Quality Based on Visual Assessment

Although visual appearance of the collagen pseudomorph is not a standard method for assessing quality, it can serve as an extremely useful preliminary indicator of quality issues (S. Garvie-Lok, pers. comm. 2019). Visual appearance was observed, and notes were recorded during the collagen isolation process to provide a general indication of the state of the collagen. As reviewed by Sealy and colleagues (2014), as bone demineralizes during preparation with the Cape Town method, well-preserved bone will form a pseudomorph that retains the shape of the original sample but that is rubbery and translucent due to the absence of bone mineral. More poorly preserved bone will fray or become extremely soft-textured because its collagen has been degraded to the point of not being able to hold together well once the supporting mineral is removed. Very poorly preserved samples will disintegrate completely. These lab notes were referred to if the other diagenetic indicators suggested poor preservation.

8.4.2 Collagen Yield

Collagen yield is the freeze-dried weight of the organic material isolated by the collagen extraction procedure as a percentage of the original dry weight of the sample. Fresh bone is approximately 22% collagen by weight (van Klinken 1999). Low yields are associated with protein loss and collagen degradation and may suggest that the remaining collagen in the sample has degraded to the point where its stable isotope values are no longer reliable. Thus, low yield can indicate that a sample is unsuitable for analysis (van Klinken, 1999). The recommended cut-off point, however, varies in the literature. Ambrose (1990) suggested a cut-off point of 2% collagen. DeNiro and Weiner (1988) as well as van Klinken (1999) suggest a cut off of 1% collagen. Conversely, high collagen yields (close to or above the normal content of fresh bone) can indicate incomplete demineralization of the bone mineral. For this study, samples with yields above 2% were accepted, samples with yields between 1% and 2% were accepted if no other indicators were marginal, and samples with yields under 1% were rejected.

8.4.3 %C and %N

%C and %N are determined by the elemental analyzer. Modern mammalian collagen has %C between 15% and 47% and %N between 5% and 17% (Ambrose, 1990); samples outside these ranges may be problematic, with low values (below 15% C and/or 5% N) especially likely to produce distorted stable isotope values.

8.4.4 Atomic C/N Ratio

The atomic C/N ratio compares the amounts of carbon and nitrogen present in the sample. Bone collagen has a high glycine content resulting in a distinct 3:1 carbon:nitrogen ratio in fresh bone. Modern bone collagen samples considered in one foundational study had ratios between 2.84 and 3.52 (DeNiro, 1985). To be considered well-preserved, DeNiro (1985) suggests that archaeological collagen should show a ratio between 2.9 and 3.6. This has been contested by van Klinken (1999) who suggests that a smaller range of 3.1-3.5 better ensures collagen preservation. As noted by (Schoeninger & Moore, 1992), C/N ratio alone cannot confirm good quality but samples that fall outside the prescribed values can be rejected. Ambrose (1990) similarly notes that well-preserved collagen tends to show C/N between 2.9 and 3.6 but cautions that this alone cannot guarantee good preservation. Dobberstein and colleagues (2009) suggests that collagen has a stable amino acid profile and C/N ratio until the collagen yield falls under 1%. For this study, samples with C/N between 3.1 and 3.5 were accepted.

8.4.5 Summary of Diagenetic Indicators

Diagenetic indicators should be considered in aggregate. Although experimental work has suggested some useful indicators, agreement on precise cut-off values is low, presumably because collagen diagenesis is an ongoing process and collagen degrades gradually rather than abruptly becoming unusable. Since diagenesis can occur for a number of reasons, it can affect collagen in different ways and, thus, can manifest differently. Thus, there is no single cut and dried method to determine collagen preservation. Instead, multiple measurements are considered as a set of indicators that together reflect the preservation quality of a sample.

8.5 Chapter Summary

Samples were selected from the Kastro Kallithea faunal assemblage based on a number of factors including context, age, and duplication of elements. In total, 36 samples were collected for processing including 30 pig samples and 6 sheep/goat samples. Although a number of protocols are available for the isolation of collagen, I decided to use the Cape Town method due to its simplicity, robusticity, and the high preservation quality of my samples. I added two additional steps to the Cape Town protocol, gelatinization and centrifugation, to further purify the collagen. This chapter also reviews diagenesis of bone, which can impact stable isotope values, and the diagenetic indicators used to assess collagen content and quality.

9 Results

This chapter presents bone collagen stable isotope data from pig, sheep, and goat remains from the site of Kastro Kallithea. The section is divided into two sections. The first section will review the results for the indicators used to assess diagenesis and bone collagen preservation. The second will present the $\delta^{13}C$ and $\delta^{15}N$ data with limited interpretation. The age of the pigs, context, and dietary relationship to the sheep and goat samples will be briefly discussed. This preliminary consideration demonstrates that the isotopic values of the pigs are clustered closely and that the sheep and goat samples analyzed appear to be isotopically similar to the pigs. The data presented in this chapter will be analyzed and discussed in Chapter 9.

9.1 Diagenetic Indicators

A total of 36 pig, sheep, and goat bone samples were analyzed as part of this study. All of the collagen samples passed the quality indicator checks discussed in Section 7.5. The results of the quality tests can be found in Table 8.1. Sample yield, atomic C/N ratio, and carbon and nitrogen content were all considered. I checked for any apparent relationships between stable isotope values and preservation indicators and none were noted.

The samples have collagen yields ranging from 1.25% to 9.78% with an average of 5.65% (Table 8.1). As previously noted, the accepted values for collagen yield are those above 1% with fresh bone producing a yield of roughly 22% (van Klinken, 1999). No samples failed this 1% yield criterion. Samples with yields below 2% (there was only one of these, MKK28 at 1.25%) were flagged and their yield and stable isotope values considered in relation to the other indicators to determine collagen quality.

The atomic C/N ratio of samples compares the amount of carbon to the amount of nitrogen in each sample. Acceptable values (see Section 7.5) are between 2.9 and 3.6 DeNiro, 1985), with some authors suggesting a smaller range of 3.1-3.5 to ensure better preserved collagen (van Klinken, 1999). The samples tested have a range of 3.16 to 3.32 – all in the acceptable range for archaeological collagen even by the tighter criteria.

Values of wt%C for the samples are fairly uniform with a range of 40.5% to 45.56% and an average of 43.48% (Table 1). All of the samples fall in the measured ranges for modern mammalian collagen of 15% to 47%. wt%N was similarly uniform with a range of 14.28% to 16.81% and a mean of 15.68% (Table 1). All of the samples fall in the accepted range of 5% to 17%. Together with the other indicators, these values suggest that all samples are acceptably preserved.

MKK28, which had a low collagen yield and was noted as being highly fragmented during the collagen preparation, passed all of the other quality indicator checks and has thus been included in the data set.

9.2 δ^{13}C and δ^{15}N Data

This section will present the δ^{13}C and δ^{15}N data for the pig, sheep, and goat collagen samples. The data are compared by species and through two additional variables, find context and age at death, to see if these variables appear to impact the isotopic values.

Table 8.1: Collagen yield, δ13C and δ15N values, atomic C/N ratio, carbon content (wt%), and nitrogen content (wt%) for the bone collagen samples.

Sample Number	*Species*	*Yield (%)*	*$\delta^{13}C$ (‰ VPDB)*	*$\delta^{15}N$ (‰ AIR)*	*Atomic C/N*	*C Content (wt%)*	*N Content (wt%)*
MKK01	Pig	3.55	-19.8	45.0	3.23	43.41	15.66
MKK02	Pig	2.46	-19.7	7.3	3.33	41.02	14.35
MKK03	Pig	4.62	-20.3	5.3	3.21	44.95	16.32
MKK04	Pig	4.73	-20.7	6.0	3.25	42.44	15.22
MKK05	Pig	6.75	-20.0	6.0	3.19	45.59	16.66
MKK06	Pig	8.50	-19.3	4.3	3.24	44.50	16.02
MKK07	Pig	6.50	-20.3	6.9	3.27	42.55	15.19
MKK08	Pig	5.22	-20.0	4.0	3.26	42.55	15.20
MKK09	Pig	8.89	-20.4	1.6	3.22	45.16	16.37
MKK10	Pig	7.97	-20.1	4.8	3.22	43.38	15.70
MKK11	Pig	8.72	-20.7	5.4	3.17	45.41	16.69
MKK12	Pig	4.09	-21.2	5.7	3.27	41.67	14.87
MKK13	Pig	9.01	-18.5	4.9	3.22	45.34	16.42
MKK14	Pig	5.57	-20.6	6.9	3.25	41.81	14.99
MKK15	Pig	2.81	-21.3	6.8	3.28	42.77	15.22
MKK16	Pig	4.58	-20.0	7.1	3.27	43.90	15.64
MKK17	Pig	4.34	-18.5	7.7	3.24	43.08	15.51
MKK18	Pig	9.24	-20.1	3.8	3.16	45.56	16.79
MKK19	Pig	2.46	-20.7	5.4	3.25	44.26	15.89
MKK20	Pig	4.36	-21.0	7.5	3.23	42.83	15.45
MKK21	Pig	7.02	-21.3	6.6	3.22	41.08	14.87
MKK22	Pig	7.25	-20.7	6.1	3.23	42.85	15.48
MKK23	Pig	4.09	-20.7	5.5	3.25	43.38	15.55
MKK24	Pig	6.52	-20.0	4.3	3.22	44.40	16.07
MKK25	Pig	9.78	-19.7	6.4	3.17	45.69	16.81
MKK26	Pig	9.07	-20.5	5.6	3.17	45.44	16.70
MKK27	Pig	6.94	-19.7	4.5	3.16	44.80	16.51
MKK28	Pig	1.25	-20.6	5.6	3.32	42.37	14.90
MKK29	Pig	4.79	-20.6	5.6	3.32	41.53	14.60
MKK30	Pig	3.65	-20.3	7.0	3.26	42.93	15.37
MKK31	Goat	5.65	-20.1	5.1	3.21	44.99	16.34
MKK32	Sheep	5.01	-20.2	6.3	3.21	43.25	15.70
MKK33	Sheep	2.67	-17.8	6.9	3.27	40.05	14.28
MKK34	Sheep	4.94	-20.6	4.4	3.23	43.15	15.57
MKK35	Sheep/Goat	6.34	-20.9	5.4	3.21	44.20	16.05
MKK36	Sheep	4.14	-20.3	6.4	3.26	42.95	15.38

A comparison of the pig and sheep/goat collagen $\delta^{13}C$ and $\delta^{15}N$ values provides a general understanding of the data (Figure 8.1). The pig samples have a $\delta^{13}C$ range of -21.3‰ to -18.4‰ with a mean of -20.5 ± 0.7‰ and a $\delta^{15}N$ range of 1.4‰ to 7.6‰ with a mean of 5.6 ± 1.3‰ (Table 8.2). The sheep/goat samples have a $\delta^{13}C$ range of -20.9‰ to -17.8‰ with a mean of -20.0 ± 1.1‰ and a $\delta^{15}N$ range of 4.4‰ to 6.9‰ with a mean of 5.7 ± 1.0‰ (Table 8.2). When the data are plotted (Figure 8.1) the pigs can be seen to have a broader distribution of $\delta^{13}C$ and $\delta^{15}N$ values, but it is unclear if this means anything or if this is just an artifact of sampling (see Chapter 9 for further discussion of this point).

Although three of the samples (two pigs and one sheep/goat) stand out based on their high $\delta^{13}C$ values, they are only separated from the main grouping of values by about 1.5‰. The scale of the chart makes the separation look large, but as will be discussed in the next chapter it is not major in the context of overall variation in Greek faunal taxa and does not likely correspond to a major difference in diets.

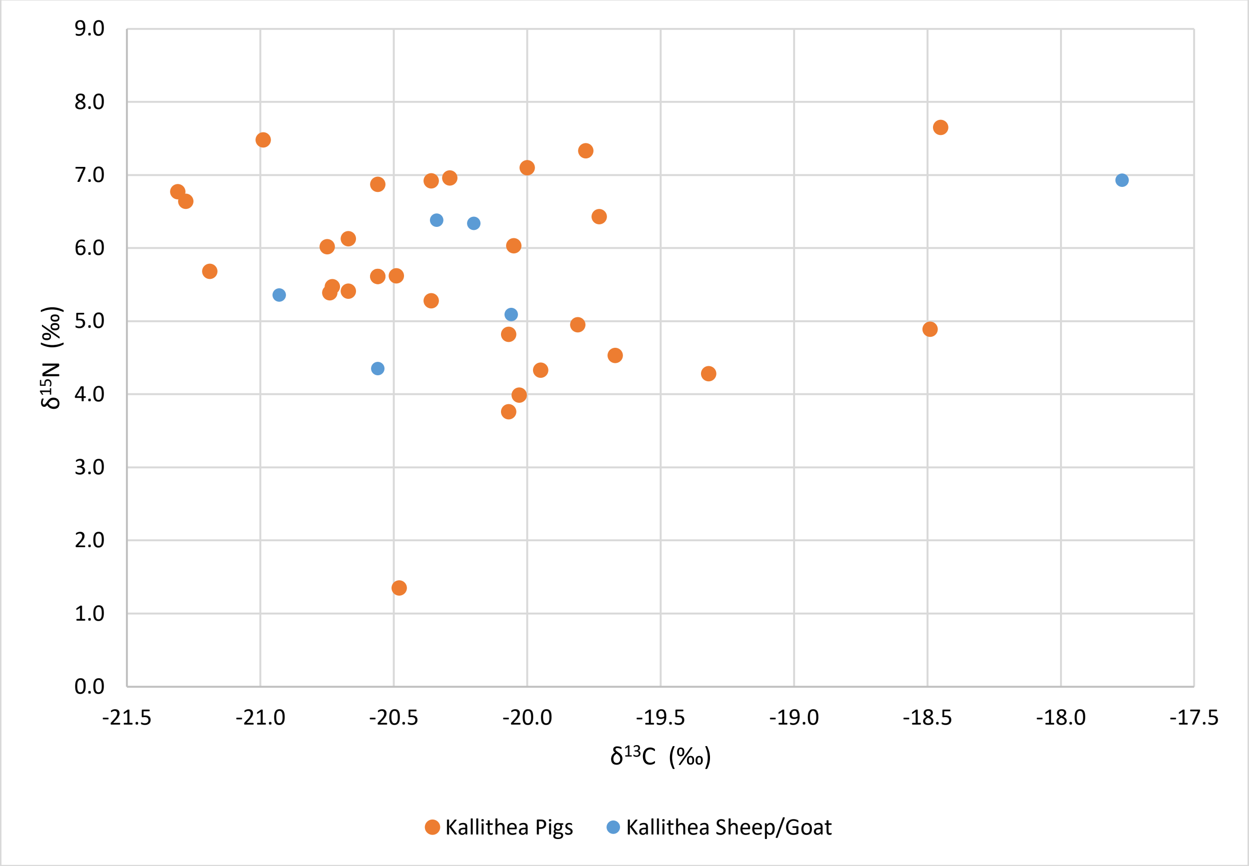

Figure 8.1: Pig and sheep/goat collagen δ^{13}C and δ^{15}N values.

Table 8.2: Mean δ^{13}C and δ^{15}N values and standard deviations for the pigs and sheep / goat samples from Kastro Kallithea.

Species	*Average $\delta^{13}C$*	*Standard Deviation $\delta^{13}C$*	*Average $\delta^{15}N$*	*Standard Deviation $\delta^{15}N$*
Pig (n=30)	-20.3	0.7	5.6	1.3
Sheep / Goat (n=6)	-20.0	1.1	5.7	1.0

Figure 8.2 compares the pig collagen δ^{13}C and δ^{15}N values between the Building 10 (orange) and Acropolis building (green) contexts. The two pigs sampled from the Acropolis

Building are isotopically similar to the pigs from Building 10 (n=28). The pigs from Building 10 have a $\delta^{13}C$ range of -21.3‰ to -18.4‰ with an average of -20.2 ± 0.7‰. The $\delta^{15}N$ values of the Building 10 pigs are less clustered with a range of 1.4‰ to 7.6‰ and an average of 5.6‰ ± 1.4‰. The pigs from the Acropolis Building have $\delta^{13}C$ values of -20.6‰ and -20.3‰ and $\delta^{15}N$ values of 5.6‰ and 7.0‰. Thus, the samples from the Acropolis Building are isotopically very similar to one another and fall within the central distribution of Building 10 values.

A comparison of the pig collagen $\delta^{13}C$ and $\delta^{15}N$ values between the two phases of occupation in Building 10 discussed in Chapter 5 suggests similar diets between the two phases (Figure 8.3). The phase 1 samples have an average $\delta^{13}C$ of -20.2‰ ± 0.7‰ and an average $\delta^{15}N$ value of 5.6‰ ± 1.4‰ whereas the samples from the second phase have averages of -20.1‰ ± 0.5‰ and 5.2‰ ± 0.6‰ respectively. The three samples from the second phase of occupation (in green) appear to be isotopically similar to the Building 10 samples. Due to the limited number of phase two samples, though, any interpretation of these results is tentative.

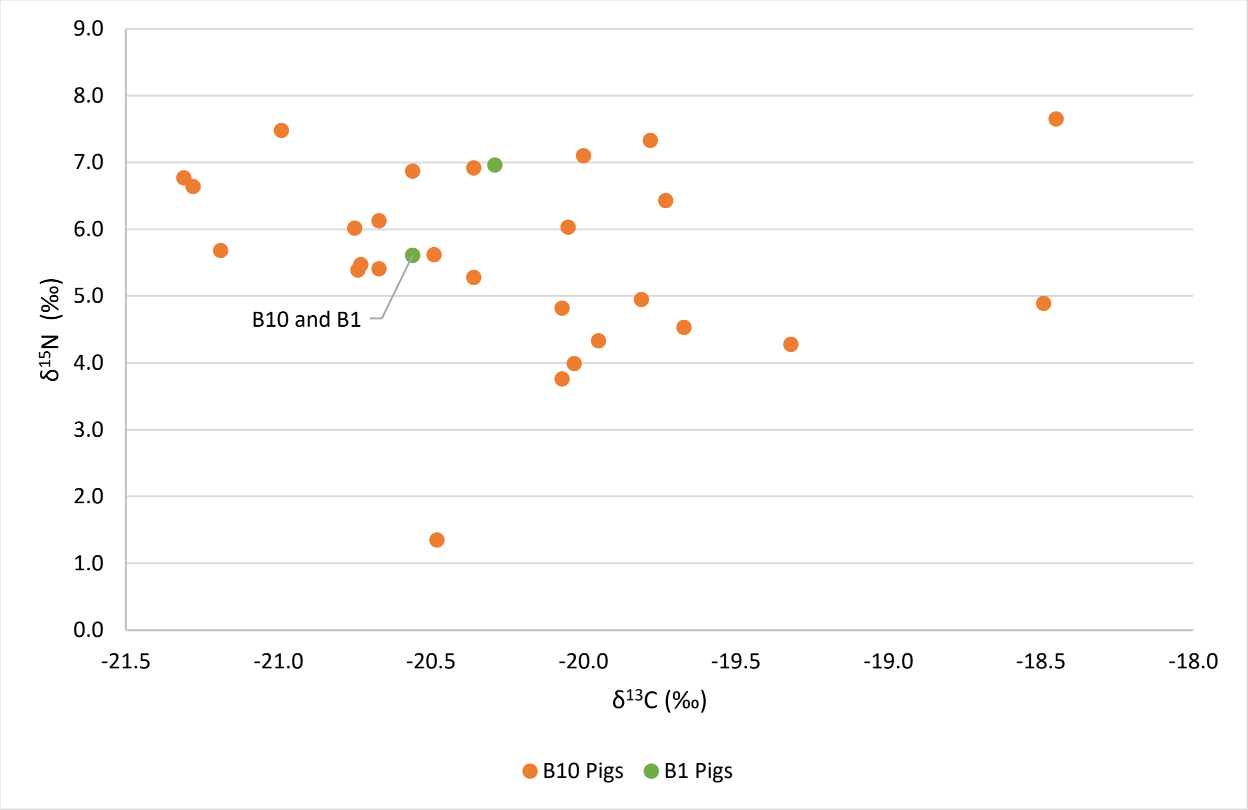

Figure 8.2: Pig collagen $\delta^{13}C$ and $\delta^{15}N$ values for the samples from Building 10 samples and the Acropolis Building 1 samples.

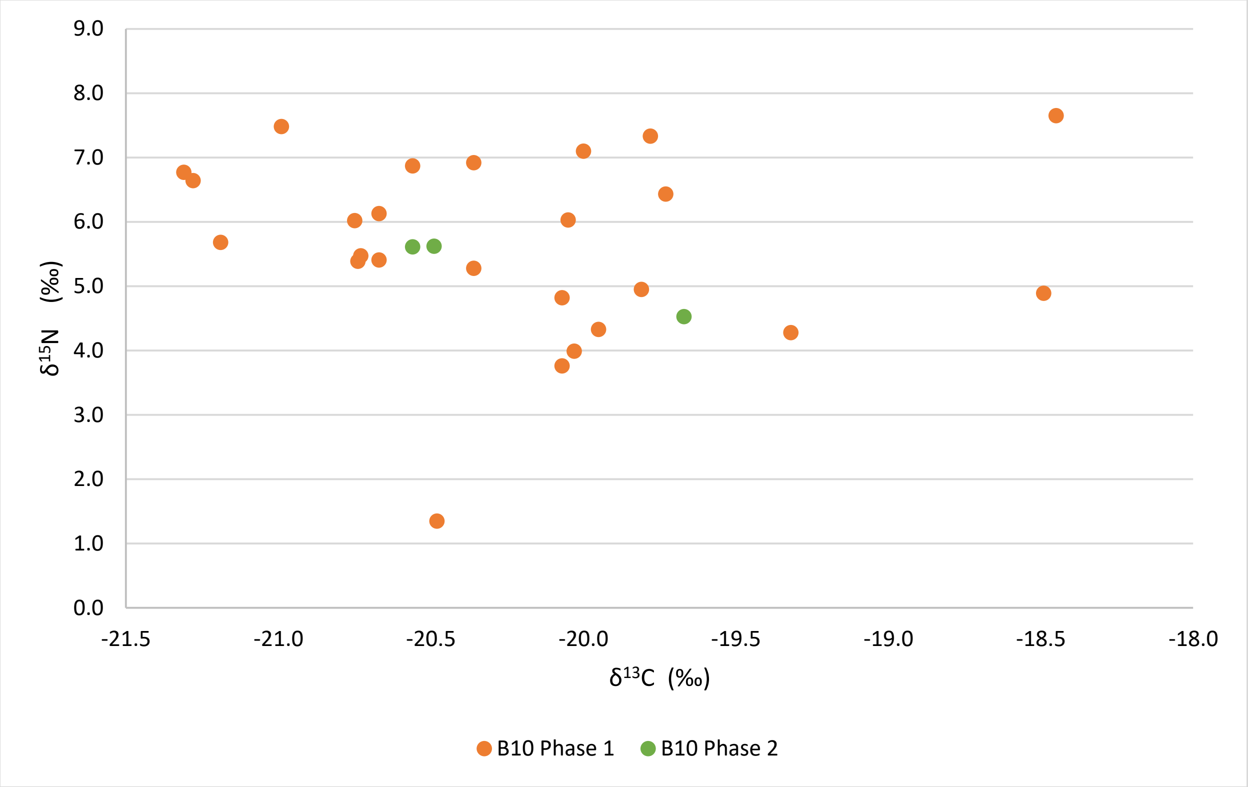

Figure 8.3: Pig bone collagen δ^{13}C and δ^{15}N values of the two phases of Building 10: phase one (orange) and phase two (green).

Figure 8.4 compares the different ages of the pigs in categories of fetal/neonate (blue), juvenile (orange), and adult (grey). The two fetal/neonate samples differ from each other and from the adult and juvenile populations. The juvenile and adult age categories overlap substantially. The fetal/neonate samples are slightly different from the older animals, especially in the case of the animal with very low δ^{15}N. With only two examples, no overall patterning is observable, but the values are still interesting. Some potential reasons for unusual values in fetal animals will be discussed in the following chapter.

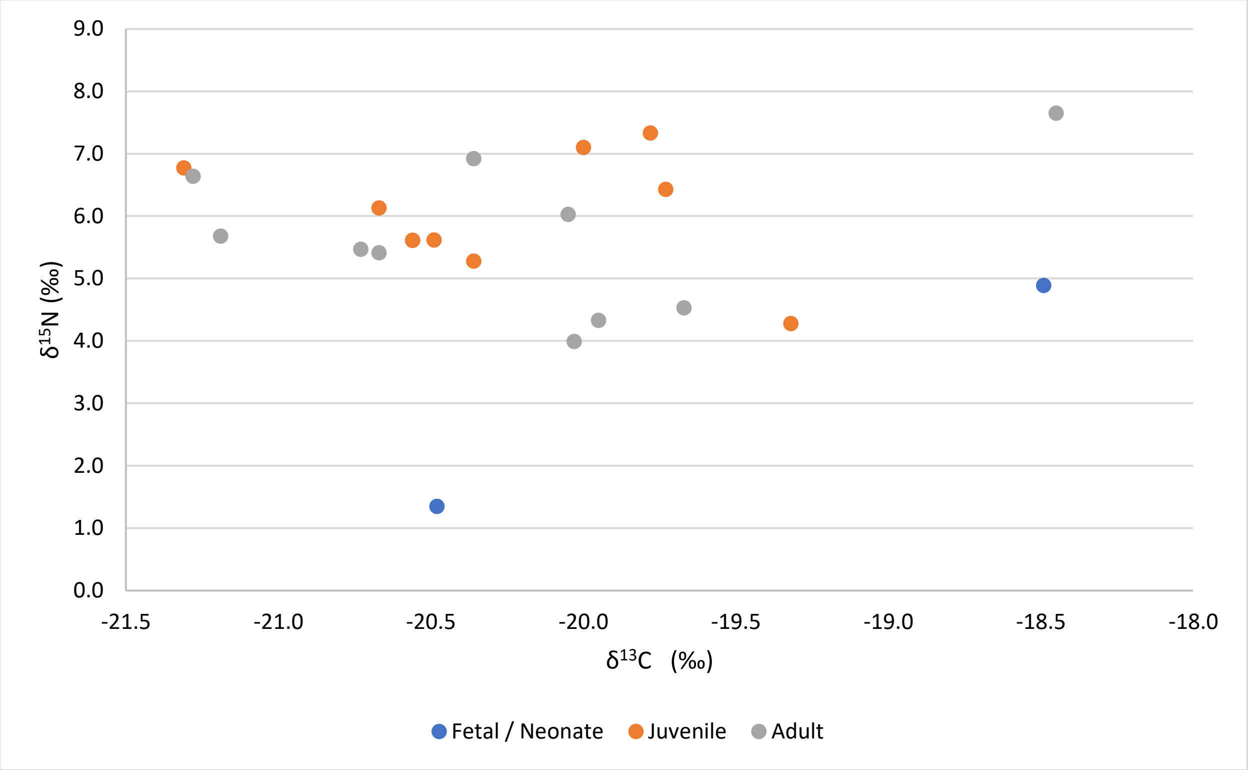

Figure 8.4: Pig bone collagen δ^{13}C and δ^{15}N values of three different age groups fetal / neonate (blue), juvenile (orange), adult (light grey).

9.3 Chapter Summary

This chapter reviewed the δ^{13}C and δ^{15}N bone collagen data from the pigs, sheep, and goat sampled from Kastro Kallithea. All of the samples passed the collagen quality indicator checks outlined in Section 7.5 and are considered in the study. The δ^{13}C and δ^{15}N data for pigs and sheep/goat samples were compared, finding similar isotopic values. The values for Building 10 and the Acropolis Building were also compared, as were the two occupational phases of Building 10; neither of these comparisons showed apparent differences, though limited sample sizes make it difficult to draw any conclusions. Finally, the δ^{13}C and δ^{15}N data was compared for three different age groups (fetal/neonate, juvenile, and adult). Both of the fetal/neonate samples fall away from the main group, though the small sample size makes it impossible to postulate any general trend. The juvenile and adult samples appear to be isotopically similar. The implications of all of this data will be considered in the following chapter.

10 Discussion

This chapter will analyze the data presented in the previous chapter, contextualizing the results with information from the background chapters. The main question of this study was what types of pig husbandry practices were used at Kastro Kallithea. My data suggests an extensive form of management with free-ranging pigs. I will compare the different factors including time period, age of animal, and context presented in the previous chapter, but given the limited number of comparative samples available, this discussion will be limited. I will then compare the results of this study to other isotopic studies of pigs from different time periods and regions in Greece, which show both similar and different husbandry practices to those at Kallithea. Finally, I will compare the pigs to other fauna and human remains from Thessaly.

10.1 Pig Husbandry at Kastro Kallithea

The sheep/goat samples included in the study will be considered first as they act as the control of what to expect of a local plant-based diet. The sheep/goat were likely herded animals and would graze on available vegetation. The $\delta^{13}C$ and $\delta^{15}N$ data agree with a predominately C_3 diet, with expected $\delta^{15}N$ levels for herbivorous animals.

Regarding the pig samples, the results of this study suggest than an extensive husbandry strategy was used for the animals at Kastro Kallithea, using a free-range subsistence method. The $\delta^{13}C$ and $\delta^{15}N$ data agree with a predominately C_3 diet, with $\delta^{15}N$ values suggestive of foraging and rooting.

Beyond the ethnographic studies discussed in Chapter 4, there is little scholarship regarding the diet of free-range pigs in Greece. There is, however, more information on the diet of wild boars; given their close relationship, this can act as a proxy by which the likely diets of domesticated free-range pigs can be understood. A review by Schley and Roper (2003), based on stomach content and fecal matter analyses, found that wild boars in Western Europe had a bulk diet of primarily plant matter separated into four categories: mast, roots, green plant matter, and agricultural crops. The boars were found to always incorporate some form of high energy food such as acorns, beechnuts, olives, or agricultural grain in their diet. In terms of non-plant dietary items, wild boars consume insects, earthworms, birds, and mammals most consistently, but also eat amphibians, reptiles, gastropods, and myriapods (Schley & Roper, 2003). Although the diet of wild boar in Western Europe cannot be assumed to be fully analogous to the free-range diet of domesticated Greek pigs, it provides a baseline for extrapolating possible diets. Domesticated pigs would likely be controlled and foddered. Unlike wild boars, their access to agricultural products would likely be normally limited to waste products made available by humans. Thus, free-range pigs would be expected to have $\delta^{15}N$ values consistent with a largely plant-based diet, with $\delta^{13}C$ values predominately representing a C_3 diet consistent with the plants found in forested regions as well as most of those grown for agricultural purposes. This matches almost exactly with the $\delta^{13}C$ and $\delta^{15}N$ values found for the Kastro Kallithea pigs. A penning signal, conversely, would likely show higher $\delta^{15}N$ as penned pigs are often reported as being fed kitchen and human waste. Kitchen waste would likely include animal products such as bone, spoiled dairy, or byproducts of dairy manufacturing all of which would raise the $\delta^{15}N$ values of the animals. Actual human waste would increase the $\delta^{15}N$ even more as feces and urine appear to have $\delta^{15}N$ values elevated over the diet (Kuhnle et al., 2013). Foddered animals would also likely be more homogenous isotopically as they would be fed a consistent diet with less variation from consuming different foraged foods. The results of this study show what is likely a single method or style of animal husbandry being implemented, with the variation within the sample population resulting from the animals foraging different food sources.

10.1.1 Building 10

One unique aspect of this study is the resolution of animal husbandry practices from a single domestic structure. As previously mentioned, many isotopic studies in Greece include a variety of animals, when possible, to better understand human diet. These studies, however, normally only study a number of each species from the whole site. By sampling 28 pig bones from a single building, we can draw more conclusions about husbandry practices at Building 10, and we are able to consider other forms of evidence more deeply with respect to the isotopic data.

10.1.1.1 Phase One and Two

As discussed in Chapter 5, there were two occupational phases of Building 10, spanning roughly one hundred years. Three of the samples I analyzed are from the second phase of occupation, from the only set of rooms (Room 4-1, 4-2, 2, and 2a) which the excavators are certain represent material from the second occupation. Based on the small number of samples tested, it is difficult to see any pattern in the values. It appears, however, that the pigs are isotopically similar to those of the first occupational phase. This suggests a similar diet and, perhaps, similar animal husbandry practices being implemented during both phases of occupation. This is interesting as it is not certain whether the population inhabiting Kallithea were similar in ethnicity and cultural habits for both occupational phases.

10.1.2 Acropolis Building 1

Since only two samples were tested from the Acropolis Building 1, it is not possible to conclude that these pigs were reared similarly to those at Building 10. The isotopic values of the two samples tested, however, are very close to the Building 10 mean, suggesting a similar dietary composition. It is possible that the pig remains found at the acropolis were from the same herd as those recovered from Building 10. As previously mentioned, the acropolis at Kastro Kallithea has not been fully excavated or studied so there is little contextual information. However, based on the presence of a sanctuary on the acropolis and the large amount of faunal bone recovered from the test trenches inside and directly outside the Acropolis Building 1 walls, it is likely that the faunal remains are from either animal sacrifice or feasting associated with sacrifice.

10.1.3 Ages of Animals

There are no observable differences between the pigs classified as juvenile and adult. As discussed in Chapter 6, it is possible that pigs do not show nursing-related δ^{15}N elevation. Even if they do show elevation, the lack of juvenile-adult differences in this sample is not surprising. Pigs naturally wean at 6-8 months and the classification juvenile extends to around two years of age, potentially blurring any nursing or weaning signal that may be present. Beyond this, juveniles and adults would be expected to have similar diets and, thus, appear similar isotopically.

The two fetal/neonate samples are isotopically different with one displaying a typical δ^{13}C value for the group but an unusually low δ^{15}N value and the other with a slightly elevated δ^{13}C value relative to other samples and a typical δ^{15}N value. Although these are interesting regarding debates of isotopic values of fetal tissue *in utero*, with only two samples it is difficult to say anything about them.

Age-related differences in diet were not expected, especially in a free-ranging husbandry scheme. Although a nursing signal was suggested as a possibility, the age at which pigs wean (approximately 6-8 months, sometimes earlier if dictated by humans) is too narrow a time period when compared to the age estimates; more specific age estimations would be needed to examine nursing and weaning patterns.

10.1.4 Reasons for Variation

Although the samples form a cluster suggestive of free-range husbandry practices, there is still a notable variation in both $\delta^{13}C$ and $\delta^{15}N$ values. As previously mentioned, free-range husbandry practices can encompass a large number of specific husbandry practices. Thus, there are a number of potential reasons that could cause the variation in isotopic values seen in the Kastro Kallithea pigs. I will discuss feeding environments, foddering, and fungi below as some of the possible reasons for the variation.

10.1.4.1 Feeding Environments

One of the possible sources of variation is different feeding environments. There would have been seasonal changes in diet based on availability of food. As reviewed in Chapter 4, ethnographic studies commonly mention changes in diet with the seasons. This can include changes in access to a forested environment as opposed to an agricultural field. The differences could also reflect changes in environment over a longer time span as the samples are representative of at least 100 years of pig husbandry based on the dating of the site. Thus, the differences could be due to yearly changes in food availability.

10.1.4.2 Foddering

Although the basis of extensive, free-range animal management does not appear to lend itself to foddering animals, the ethnographic studies (Chapter 4) indicate that extensively managed animals could still be foddered at times. Foddering could supplement the diet when food was scarce (Albarella et al., 2011; Hadjikoumis, 2012; Halstead & Isaakidou, 2011), or keep the pigs used to human presence (Albarella et al., 2011). In both scenarios, limited foddering would not have drastically changed the lifetime δ^{13}C and δ^{15}N averages of the pigs. It could, however, contribute to minor inter-individual variation in δ^{13}C and δ^{15}N values, especially if the fodder supplied did not remain consistent over time. It is unclear what the fodder would have been composed of; ethnographic studies suggest foddering can include a variety of foods including agricultural grain but also can include acorns gathered for the pigs.

10.1.4.3 Fungi

Boars consume fungi as part of their diets based on stomach content and fecal matter analyses (Barescut et al., 2009; Hohmann & Huckschlag, 2005; Piattoni et al., 2016). As reviewed by Schley and Roper (2003), two studies from the Mediterranean found fungi in 46% to 60% of boar fecal samples (Abáigar, 1993; Fournier-Chambrillon et al., 1996). Other studies, conversely, have not reported fungi present in stomach content and fecal matter analyses (Schley & Roper, 2003). Stomach content analysis, however, records diet close to death and the high digestibility of fungi means that evidence may not exist in fecal matter, so it is possible that the boars did eat fungi even if they were not detected in these studies (Schley & Roper, 2003). Fungi have been suggested to have dietary importance for pigs in three isotopic studies: Hamilton and colleagues (2009), Hamilton and Thomas (2012), and Millard and colleagues (2013).

Hamilton and Thomas (2012) suggested that the differences in $\delta^{13}C$ values seen between pig and other domesticates studied in Neolithic and Iron Age Britain could be a result of pigs foraging fungi as a part of their diet. As reviewed by O'Regan and colleagues (2016), fungi are isotopically complex and not fully understood. Their complexity stems from a number of causes, including the biological diversity of edible fungi, which are found in two different fungal phyla, and the fact that fungi can consume food from different trophic levels (Steffan et al., 2015) making understanding fractionation difficult. The consumption of fungi by pigs typically occurs in woodland environments with the two main types of fungi present being saprotrophic fungi that feed on dead wood and mycorrhizal fungi which obtain nutrients through plant roots (Hamilton & Thomas, 2012). Saprotrophic and mycorrhizal fungi have variable $\delta^{13}C$ values with a tendency to be ^{13}C enriched (Kalač, 2009). Hamilton and Thomas (2012) estimate woodland fungi to be, on average, 4-6‰ $\delta^{13}C$ elevated over photosynthetic plants. Saprotrophic fungi tend to have higher $\delta^{13}C$ and lower $\delta^{15}N$ values than mycorrhizal fungi (Hobbie et al., 1999). Fungi are high in protein; a study of 47 species of Macedonian mushrooms resulted in an average crude protein content of 32.6% of dry matter (Petrovska, 2001), with some species having almost 60% of the dry matter (Barros et al., 2008). The high protein content suggests that regular consumption of fungi could impact $\delta^{15}N$ values of bone collagen.

Thus, it is possible that some of the variation in the pigs' $\delta^{13}C$ and $\delta^{15}N$ values could be from pigs consuming fungi. Since there is no comprehensive review of fungi currently present in ancient Greece, it is difficult to ascertain the exact effect that fungus consumption would have on the $\delta^{13}C$ and $\delta^{15}N$ values of the pigs, however, any measurable effect could explain some of the variation found in the Kallithea pigs. This is interesting as the other explanations for the variation involve human control whereas fungus consumption is more based on the pigs' chosen diet.

10.2 Dispersal of Pig Data Compared to Sheep/Goat Data

This purpose of this comparison is to determine whether the pig samples appear to be more dispersed isotopically than the sheep/goat samples due to actual differences in diet or if it is an artifact of small sample sizes. Due to the limited amount of comparison possible with only six sheep/goat samples, I will also consider six individuals tested by Bishop (in prep) for enamel carbonate $\delta^{13}C$. Three of these samples are from the same animals tested in this study. The enamel carbonate samples were taken as microsamples to examine seasonal patterning, so the values have been averaged to produce an average spanning the formation period of the tooth (Table 9.1). As can be seen from Tables 9.1 and 9.2, the scatter for pigs is slightly higher than that of the sheep/goat but not by much.

Table 9.1: Averaged δ^{13}C values for sheep/goat enamel carbonate. Data from Bishop (in prep).

Sample Number	*Average δ^{13}C (‰)*	
SG03	-9.9	
*SG06**	-9.4	
SG08	-10.0	
*SG11**	-10.0	
SG16	-8.8	
SG21	-9.2	
*SG23**	-10.4	
	Spread	1.6

* These animals are also sampled in this study.

Table 9.2: Average δ^{13}C spread for the pig and sheep/goat from Kastro Kallithea

Species	*Tissue Fraction*	*δ^{13}C Spread*
Sheep/ Goat	Enamel Carbonate	1.6
Sheep / Goat	Bone Collagen	3.2
Pig	Bone Collagen	2.9

10.3 Comparison to pigs at other sites

A comparison of the δ^{13}C and δ^{15}N values of pigs at Kallithea with those from other sites is important to see how the results from this study compare to those of other studies. Contextualizing the data in this way enhances the interpretation. Because of the scarcity of prior research on pigs the comparison of the δ^{13}C and δ^{15}N data from Kallithea will have to use studies outside the region and the time period. Roman Corinth and a number of sites from the Byzantine period will be discussed below.

10.3.1 Roman Corinth

Figure 9.1 compares the pigs from Kastro Kallithea to fauna from Roman Corinth (Garvie-Lok et al., 2016). Although the sheep/goat remains show similar isotopic signals to the Kallithea pigs and sheep/goat, the Roman Corinth pigs appear to be distinctive. Although this may be due to a limited sample size of Corinth pigs, it suggests a different food source and perhaps a different type of management than seen at Kallithea.

One of the Roman Corinth pigs has a low $\delta^{15}N$ value, similar to one of the Kallithea juvenile/neonate samples. Interestingly, the Roman Corinth pig was not a juvenile but was estimated to be an adult (Garvie-Lok, pers. comm., May 2019). This suggests that other factors may be impacting the $\delta^{15}N$ value of the Kallithea piglet beyond its stage of development.

This comparison is important as it confirms that not all pigs will look isotopically similar to those at Kallithea allowing more confidence in my interpretation. It also shows that having larger sample numbers is beneficial as it allows such comparisons: since there are 30 pig samples from Kallithea, it can be posited that there are differences in husbandry practices between the two sites even with the small number of samples from Roman Corinth. To actually postulate the diet of pigs in Roman Corinth, however, more samples from that site would be needed.

10.3.2 Byzantine Period

Figure 9.2 compares the pigs from Kastro Kallithea to those of Byzantine Athens (Garvie-Lok, 2002), Corinth (Garvie-Lok, 2002), Kastella (Bourbou & Richards, 2007), and

Mytilene (Garvie-Lok, 2002). The samples from all of the sites fall into the range of those at Kastro Kallithea. The average δ^{13}C and δ^{15}N values for the Byzantine sites (Table 9.2) show how tight the data sets are especially in relation to δ^{13}C values, though the δ^{15}N values are similar too. Although the sample sizes for each of the respective sites is small, the isotopic similarity between the Byzantine pigs and those from Kallithea suggest a similar diet and, therefore, suggest that similar husbandry strategies may have been used.

This resolution at Kallithea is important, due to the high number of animals sampled, as it will allow comparisons to be made at sites where fewer pigs can be sampled.

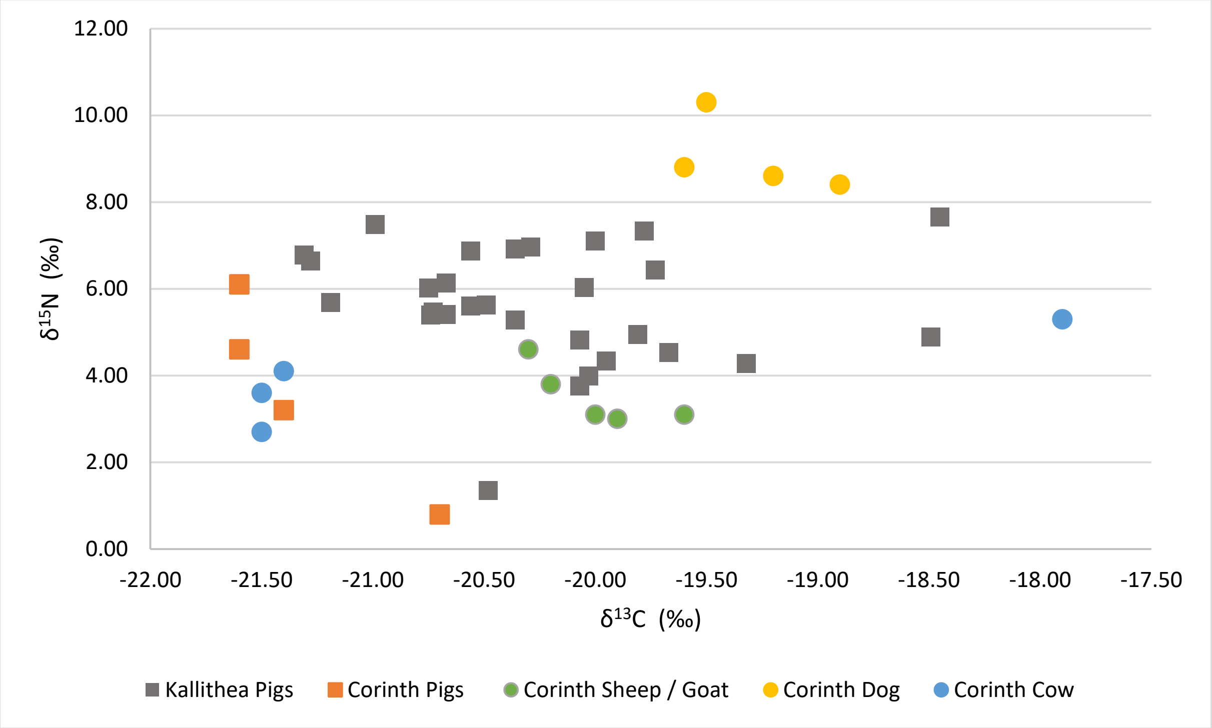

Figure 9.1: δ13C and δ15N values for the Kallithea pigs as well as fauna from Roman Corinth. Roman Corinth data from Garvie-Lok et al. (2016).

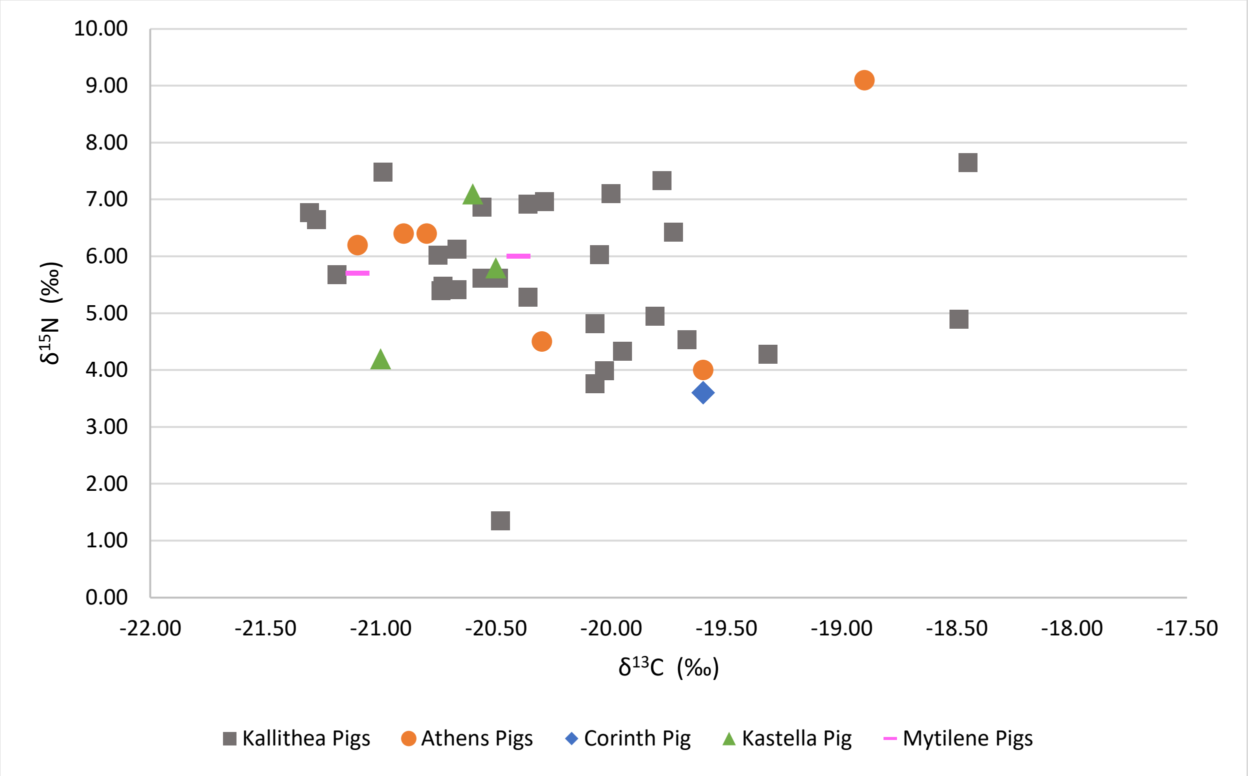

Figure 9.2: δ13C and δ15N values for the Kallithea pigs as well as fauna from the Byzantine Period. Byzantine data from Garvie-Lok (2002) and Bourbou and Richards (2007).

Table 9.3: Average δ13C and δ15N values and corresponding standard deviations from the Kastro Kallithea, Athens, Corinth, Kastella, and Mytilene.

	n	*Average $\delta^{13}C$*	*$\delta^{13}C$ STDEV*	*Average $\delta^{15}N$*	*$\delta^{15}N$ STDEV*
Kallithea	30	-20.3	0.7	5.6	1.3
Athens	6	-20.3	0.6	6.1	1.8
Corinth	1	-19.6	N/A	3.6	N/A
Kastella	3	-20.7	0.3	5.7	1.5
Mytilene	2	-20.8	0.5	5.9	0.2

10.4 Compared to New Halos

As previously mentioned, there are no other (bio)archaeological studies of pigs in Thessaly, much less Hellenistic Thessaly. There are, however, isotopic studies of faunal material from New Halos, analyzed as part of a study on human diet in Sparkes' dissertation research (Sparkes, 2017). This is an interesting comparison as Kastro Kallithea and New Halos are two Thessalian cities in Achaia Phthiotis from roughly the same time period but, as reviewed in Chapter 5, they represent different environments with Kastro Kallithea being inland and New Halos being a coastal site.

10.4.1 Sheep/Goat Comparison

By comparing the Kastro Kallithea samples to the sheep and goat from New Halos, it is apparent that the samples of sheep and goat from both sites are similar isotopically (Figure 9.3). Moreover, the sheep and goat samples from New Halos are also isotopically similar to the pigs from Kastro Kallithea. This may suggest that similar husbandry systems were occurring at both of the sites.

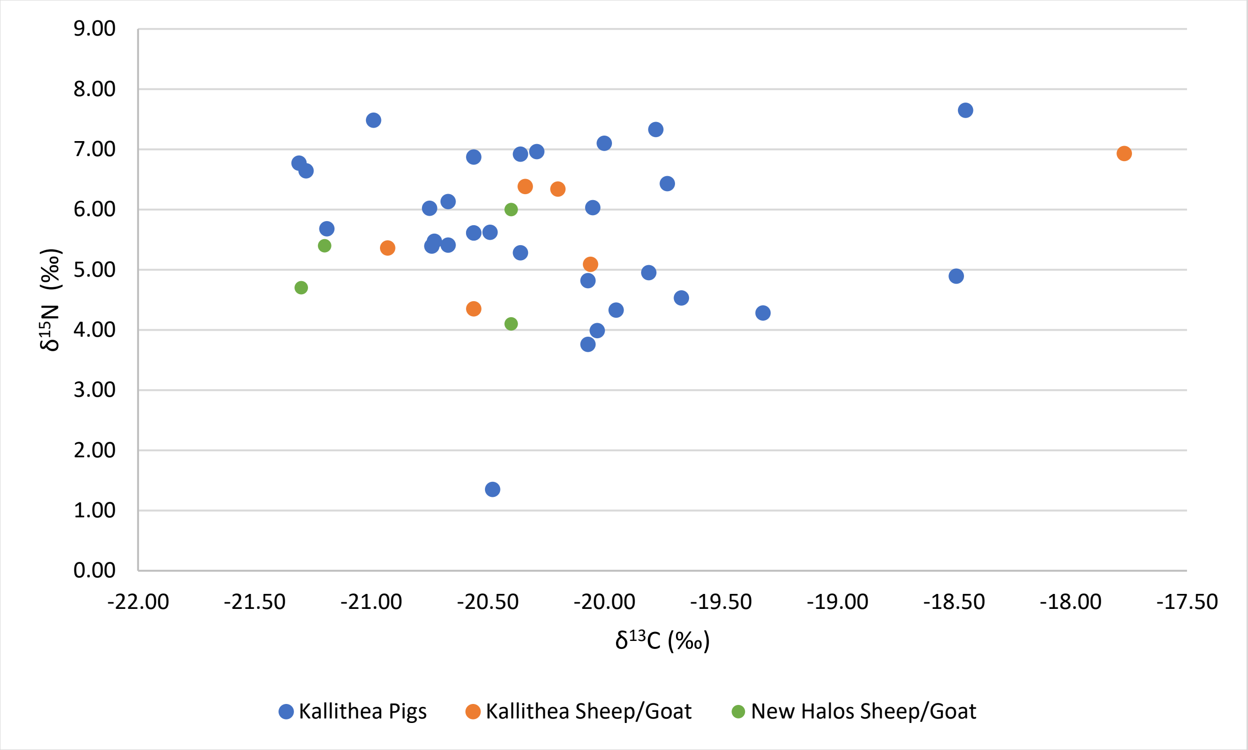

Figure 9.3: δ^{13}C and δ^{15}N values for the Kallithea pigs and sheep/goat samples and the New Halos sheep/goat.

10.4.2 Humans

The study at New Halos was focused on human diet at the site, so the diets of humans at New Halos can be compared to those of the pigs at Kastro Kallithea. Although the samples are from different sites and different environments, this is an interesting comparison as it allows a conceptualization of where human diet would likely sit in relation to the pigs. As seen in Figure 9.4, the humans sampled from New Halos have an average δ^{13}C value of -19.8‰ and δ^{15}N value of 9.3‰. This was interpreted by Sparkes (2017) to suggest a C_3 based diet with terrestrial animal products, and low-trophic marine protein being of varying importance on an individual basis. The humans fall within the δ^{13}C range of pigs but are substantially above the pigs for δ^{15}N; this agrees with the pigs having a predominately plant based diet.

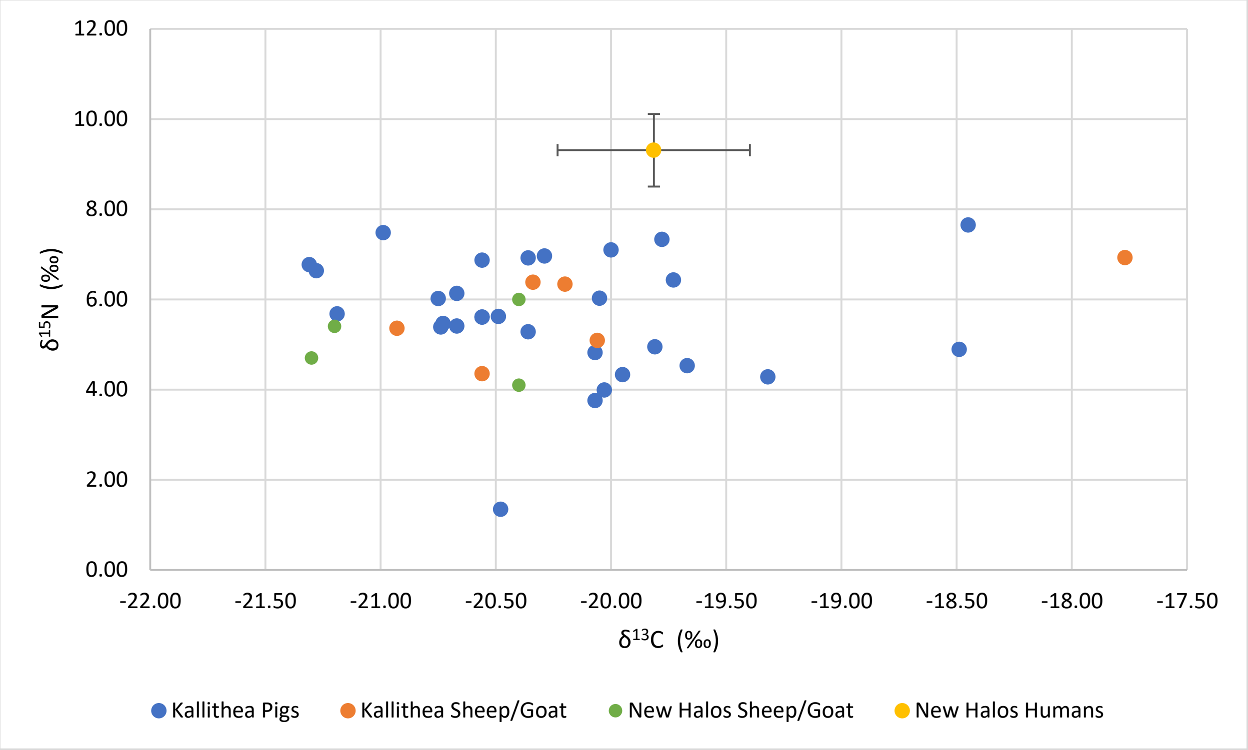

Figure 9.4: $\delta^{13}C$ and $\delta^{15}N$ values for the Kallithea pigs and sheep/goat samples and New Halos sheep/goat and human samples. New Halos data from Sparks (2017).

10.5 Pig Husbandry and Economy at Kastro Kallithea

At Building 10 and Acropolis Building 1, pig husbandry appears to have consisted of extensive management. This suggests that it was likely a specialized job as opposed to a role of the domestic sphere. This contradicts some of the primary sources that reference pig husbandry (see Chapter 4). Aristotle suggested that pigs and dogs could be grouped together as animals that live with humans; although this is possible, the pigs at Kastro Kallithea do not appear to have been eating human refuse. This study also contradicts descriptions of pig keeping in the Odyssey which depicts pigs being kept in a sty and pen (Hom. *Od*. 14.48-71). Although this likely occurred elsewhere in ancient Greece, there is no evidence for this type of penning at Kastro Kallithea.

It is interesting that there does not appear to be changes between the first and second phases of occupation (though the low sample size from the second occupation makes it difficult to know). The data does not suggest continuity in population but perhaps similar pig husbandry practices.

10.6 Chapter Summary

Overall, the data indicates that pigs from Building 10 were managed extensively, likely in similar ecological regions to the sheep and goat. No significant differences were observed between the two occupational phases of Building 10 or between Building 10 and Acropolis Building 1. The small sample size for both the second occupational phase and Acropolis Building 1 may be obscuring any differences. Potential reasons for variation within the pigs sampled from Kastro Kallithea include time period, foddering, and fungi consumption. The pigs from Kastro Kallithea were compared to the fauna and humans studied at New Halos, as well as pigs from other regions and time periods. This showed the benefit of in-depth studies of pig husbandry, as sites with fewer samples could be compared to Kallithea to get a general sense of the management strategy occurring.

11 Conclusion

11.1 Summary

In this study, stable carbon and nitrogen isotope analysis was used to infer pig husbandry practices in Hellenistic Thessaly. The goal of the study was to determine the type(s) of pig management practices used at Kastro Kallithea as related to the domestic economy. Skeletal elements from 30 pigs and six sheep/goats were sampled from a domestic (Building 10) and public (Acropolis Building 1) space. The results of the study suggest that the pigs consumed a primarily C_3 diet and were likely extensively managed. The purpose of this chapter is to summarize the findings and to offer suggestions for future research.

11.2 Pig Husbandry at Kastro Kallithea

This study presented a review of historical, archaeological, and bioarchaeological perspectives on pig husbandry. The ancient sources provided little information regarding pig management strategies; the information that does exist is highly fragmentary and not directly applicable to Kastro Kallithea, Thessaly, or the Hellenistic period. Stable isotope analysis was used to determine the diet of the pigs sampled. Due to the dietary differences that accompany individual husbandry practices, a management strategy could be inferred based on the results of the isotopic analysis. A tailored review of the foundations of stable isotope analysis was provided as well as a review of pig husbandry studies and faunal stable isotope studies in Greece. Since there are no published studies of pig husbandry studies in ancient Greece, studies from other geographic regions were used to understand how pig husbandry could be determined from stable carbon and nitrogen isotope analysis. A brief discussion of collagen extraction protocols and a background overview of diagenetic indicators was included.

The study was designed to answer questions regarding pig husbandry practices related to the domestic economy at Kastro Kallithea. Sheep/goat samples were included as an herbivorous baseline from which trophic level differences of the pigs could be understood. The pigs sampled have a mean $\delta^{13}C$ value of -20.5 ± 0.7‰ and a mean $\delta^{15}N$ value of 5.6 ± 1.3‰. The sheep and goat had a similar mean $\delta^{13}C$ value of -20.0 ± 1.1‰ and a mean $\delta^{15}N$ value of 5.7 ± 1.0‰.

The data indicates that pigs sampled in this study were managed extensively, likely in similar regions to the sheep and goat. No significant isotopic differences were observed between Building 10 and Acropolis Building 1 or between the occupational phases of Building 10. However, the potential for the small sample size for both the second occupational phase and Acropolis Building 1 to be obscuring any differences was considered. Potential reasons for variation within the pigs sampled from Kastro Kallithea include time period, foddering, and fungi consumption.

11.3 Pig Husbandry in Ancient Greece

The samples from Kastro Kallithea were also compared to those from other sites. Since there are not a plethora of studies that include samples from more than a few pigs from a single site, a limited number of sites were chosen with preference given to those in similar time periods. This comparison was initially completed to see if the results from the study were similar to that of the published literature; however, due to the high resolution of this study I was also able to suggest isotopic differences may be due to the utilization of other husbandry practices different from that at Kastro Kallithea. This suggests that the reason why ancient authors provide contradictory evidence regarding how pigs were managed is that a myriad of strategies actually existed.

11.4 Future Research

Since there are no other isotopic studies of ancient pig husbandry in Greece, a primary avenue for future research would be expanding these types of studies. Although studies of animal diet in ancient Greece do exist, the small sample sizes make comparison and inferences regarding management practices difficult and, in some cases, impossible. Beyond pigs, the addition of broader faunal stable isotope studies would help to add to our understanding of animal husbandry in ancient Greece. These studies could cover broad or narrow geographic areas, represent diachronic studies or use a limited timescale, include a number of species or focus on a specific species; the important aspect is including robust sample sizes that allow comparison between sites. It would also be beneficial for researchers using fauna as an isotopic baseline in their studies of human diet to attempt to include larger numbers of fauna in their studies (especially with multiple samples from the same species) if possible. This could not only help to improve our understanding of animal husbandry and the diversity of management practices in ancient Greece but would benefit studies of human diet as understanding baseline variation is important in understanding human isotopic variation. The development of faunal isotopic work in Greece would make comparison easier and would be beneficial as future studies can be situated in a Greek context rather than having to rely on those from other geographic regions.

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