APPLYING SYNDEMIC MODELS TO BIOARCHAEOLOGICAL RESEARCH

HEALTH'S WAYWARD SISTERS: APPLYING SYNDEMIC MODELS TO THE ANALYSIS OF DIET, NONSPECIFIC STRESS, AND MORTALITY

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LAY ABSTRACT

This research explores how syndemic models can be used to investigate interactions among health, diet, and social factors, and improve bioarchaeological understanding of past populations. Syndemic models underline that health related conditions can interact to produce synergistically worse health outcomes in specific socio-historical environments. Syndemic analysis of a medieval (10^{th}-16^{th} c. CE) Croatian skeletal sample using integrative statistical methods revealed patterns missed by traditional analysis, such as different diets and health outcomes among monks compared to laypeople buried in the cemetery. These results demonstrate that changes to bone related to stress, what someone ate, and how long they lived are deeply interconnected, and different patterns can be linked to a person's role in medieval society. Viewing different indicators of health as interconnected enriches our knowledge of ancient lives and guides future bioarchaeological research.

ABSTRACT

This thesis explores how the application of syndemic theory in bioarchaeological research necessitates a shift in the reductionist analytical frameworks that inform research, the impacts of this, and how this framework can be broadly operationalized and applied in bioarchaeological research. A syndemic model underlines the interconnected and interactive nature of health-related conditions and thus offer a more integrative and dynamic approach to interpreting health data from the past. Chapter 2 outlines the implications of adopting a syndemic model, demonstrating how it can generate new research questions and insights by shifting current discrete, reductionist analytical frameworks to more inclusive ones, and outlining how we can start applying these frameworks in bioarchaeological research broadly. Chapters 3 and 4 demonstrate how syndemic models can be applied to commonly analyzed bioarchaeological data, reify the benefits of this approach, and how it can be operationalized. This is done via multivariable statistical analyses to examine intra-population variation in diet, nonspecific stress, and mortality in the medieval (10^{th}-16^{th} centuries CE) osteological sample from Osor, Croatia.

The results reveal that multivariable approaches more effectively capture the interrelated nature of health indicators than traditional bivariate methods, uncovering nuanced patterns of interaction and intra-population variation. Notably, the monastic individuals at Osor exhibited distinct dietary practices and higher rates of nonspecific lesions yet did not experience reduced mortality typically associated with medieval monastic communities. In contrast, privileged lay individuals showed increased frailty despite their more protein and/or marine-rich diets. One area of the cemetery, Sector 6, emerged as a potentially distinct subgroup based on distinctive isotopic and demographic patterns. The results in Chapters 3 and 4 underscore the value of syndemic models and multivariable analyses in uncovering complex health dynamics and offer a replicable framework for future syndemic-oriented research in bioarchaeology and related disciplines.

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LIST OF ABBREVIATIONS AND SYMBOLS

NSL …… Nonspecific Lesions

PNBF …….. Periosteal New Bone Formation

HCl ……. Hydrochloric Acid

NaOH ……. Sodium Hydroxide

$\delta^{13}C$ …… Delta 13 Carbon

$\delta^{15}N$ …… Delta 15 Nitrogen

‰ …… Parts per thousand

VPDB ……. Vienna Pee Dee Belemnite

AIR ……. Atmospheric Nitrogen

DECLARATION OF ACADEMIC ACHIEVEMENT

I declare that I am the main contributor to all three articles that make up this thesis. Chapter two, titled "Building a Syndemic Bioarchaeology," is a co-authored paper prepared for submission. Chapter three, titled "Using Multivariable Statistical Analyses to Address Interrelated Data: An Examination of Diet, Nonspecific Stress, and Age-at-Death in a Medieval Cemetery (Osor, Croatia)" is a co-authored paper prepared for submission to the *American Journal of Human Biology*. Chapter four, titled "Intrapopulation Variation in St. Peter's Medieval (10^{th}-16^{th} Centuries) Cemetery (Osor, Croatia): A Multivariable Analysis of Diet, Nonspecific Stress, and Mortality", is a co-authored paper submitted to *Bioarchaeology International*. I am the first author for all three papers. I collected data, completed all lab work, and analyzed data with input from my co-authors on methodology and analysis where appropriate. I wrote all the first drafts and prepared the tables and figures. For Chapter Two, my co-author collaborated on writing and creating figures and tables. For chapters three and four, the co-authors collaborated on subsequent revisions.

CHAPTER 1: INTRODUCTION AND BACKGROUND

The analytical frameworks, or models, that researchers use to structure, organize, and guide research enable them to put theory into practice (Geller, 2021). These frameworks determine what questions we deem relevant, how we structure our investigations, the methods we use, what types of data we collect, and how we record and analyze that data. These considerations then determine how we learn from our data (Stodder, 2012). Bioarchaeology and its sister disciplines of paleopathology and paleoepidemiology are situated within Western social scientific disciplines that are founded upon Western scientific practices and analytical models (Shipley & Williams, 2019). These models are built upon the concept of reductionism which breaks down phenomena into their constituent parts to analyze them discretely (Shipley & Williams, 2019; Singer, 2009). Reflections of this can be seen in how bioarchaeological and related research is often siloed and commonly structured to focus on a specific type of osteological data, such as stable isotopes, degenerative disease, violence, specific infectious or metabolic diseases, etc. Within the field of bioarchaeology, however, there is growing interest in applying more integrative analytical models that account for the dynamic and interconnected relationships between the health data bioarchaeologists and others study (e.g., DeWitte et al., 2022; Mant et al., 2021; Schug & Halcrow, 2022; van Schaik & DeWitte, 2020).

Of note, syndemic theory has gained increased traction within bioarchaeology over the past 10 years, especially following the COVID-19 pandemic (Larsen & Crespo, 2022; Schug & Halcrow, 2022; van Schaik & DeWitte, 2020). Syndemic theory explains how diseases can cluster due to overarching social forces (e.g., war or poverty) and interact to produce dramatically greater impacts on health (Singer, 2009). Singer (2009) argues that embedded within syndemic theory is a paradigm shift in our understanding of disease and health-related conditions. This shift involves diseases/health-related conditions being understood as interconnected and interactive with sociocultural forces *and* other diseases/health-related conditions within complex biosocial environments, rather than as isolated entities.

This syndemic model builds upon existing biocultural models of health by highlighting processes of interaction that can manifest in specific biosocial environments and the need to consider the broader epidemiological landscapes in which a disease or health-related condition exists (Singer, 2009). Just as neglecting socio-cultural factors limited our understanding of health and disease in the past, overlooking interaction can distort the "on-the-ground and in-the-body realities" (Singer, 2009, p. xvii) that bioarchaeologists and others aim to understand (Milner & Boldsen, 2017). Indeed, many of the conditions that bioarchaeologists and others study can interact with one another. Some well-known examples include the interrelationships between nutrition and disease, the co-occurrence and interaction of metabolic diseases, and common interactions between metabolic conditions and bacterial or viral infections (Brickley et al., 2020; Brown et al., 2020; Ives, 2018; Schattmann et al., 2016; Singer, 2009).

To put syndemic theory into practice, bioarchaeologists must ensure that our analytical models align with this theoretical framework so that research can be framed and constructed in a

way that allows interactions between health-related conditions to be captured in our data. However, those traditional, discrete approaches are not the best suited for this (Singer, 2009). Examples of discrete approaches in bioarchaeological research include frequency-based approaches and research structured to focus on a single health-related condition and its relationship to social, physical, and temporal environments or trends (e.g., Newman & Gowland, 2017; Snoddy et al., 2017; Toyne, 2015). While important and illuminating, research structured this way cannot account for interconnections between diseases/health-related conditions. Following Singer's (2009) arguments, applying a syndemic theory in bioarchaeological and related research necessitates shifting our analytical models, moving from discrete to more integrative frameworks. Because analytical models are the foundation upon which we structure and create research, such a shift has wide-ranging impacts on the research questions we deem relevant, how we collect and analyze data, our conceptualization of disease and health-related conditions, and our methodologies.

To date, discussions in bioarchaeology around syndemic theory have emphasized the importance of investigating the social component of syndemic interactions, such as how structural violence/racism, social isolation, poverty, and the institutionalization of persons within asylums created conditions for syndemic disease interactions to occur (Perry & Gowland, 2022; Sattenspiel & Herring, 2010; Zuckerman et al., 2022). Research has also stressed the importance of syndemic theory for understanding historic epidemics (Dimka et al., 2022; Schug & Halcrow, 2022), such as the Black Death (e.g., DeWitte et al., 2022; van Schaik & DeWitte, 2020; Yaussy et al., 2016), the 1918 influenza pandemic (e.g., Herring & Sattenspiel, 2007; Sattenspiel & Mamelund, 2012; van Doren & Kelmelis, 2023), as well as major epidemiological transitions (e.g., van Doren, 2023). This work provides strong examples of how researchers can and have undertaken this kind of work. There has yet to be work outlining the explicit ways in which applying a syndemic analytical frameworks, or syndemic model, impacts the existing analytical frameworks bioarchaeologists use. This includes how a syndemic analytical model has far-reaching implications for how we research disease and health-related conditions beyond the context of historic epidemics, how we construct our methods, data collection, and analyses, and how this model impacts the questions and data we consider relevant for our research.

My doctoral research explores how a syndemic analytical model impacts existing analytical frameworks and conceptualizations of disease/health-related conditions in bioarchaeology, and how this model can be operationalized more broadly within our research. To do so, I put a syndemic model into practice by using multivariable statistical analyses to examine intra-population variation in diet, nonspecific stress, and age-at-death – three highly interrelated types of health data – in a medieval (10^{th}-16^{th} c. CE) osteological sample from Osor, Croatia. This research is centered around three core questions:

1. On a conceptual level, how does the application of a syndemic model shift the analytical frameworks employed in bioarchaeological research, and what are the implications of this for how we frame, structure, and conduct research on disease and health-related conditions within the field as a whole?

2. How can a syndemic model be applied to relevant research beyond historic epidemics to commonly analyzed interrelated health data, such as diet, nonspecific stress, and mortality risk, by leveraging multivariable statistical analyses?
3. How does applying this syndemic model allow us to glean more from commonly analyzed interrelated data?

1.1 SYNDEMIC THEORY AND HEALTH-RELATED CONDITIONS

Syndemic theory was developed within the rethinking of critical medical anthropology, which re-focused on how macro-, rather than micro-, social, political, and economic systems shape health, disease, and suffering (Mendenhall, 2012; Singer & Mendenhall, 2022). The first "syndemic" to be coined was the SAVA syndemic (substance abuse, violence, and HIV/AIDS) amongst inner-city populations by Merrill Singer (1996). Singer (1996) argues that these concurrent epidemics wreaking havoc in impoverished inner-city populations did not exist parallel to each other but were intimately intertwined within the adverse social and physical environments of poverty. He further argues that these concurrent epidemics shared a synergistic relationship where individuals who experienced one of these phenomena were at much greater risk of experiencing and/or developing the others in a way that significantly increased health burdens. Singer (1996) thus terms the phenomenon of interrelated, synergistically interacting epidemics a "syndemic".

Three core concepts underlie syndemic theory: (1) diseases can cluster by person, place, and time period; (2) when they do, they can synergistically interact to produce unique and exponential impacts on health; (3) and this happens as a result of macro-level social forces such as poverty (Singer, 2009). Therefore, when disease clustering occurs in the same space and time, it stems from the same overarching health-threatening social conditions (Tsai et al. 2017). In syndemic theory, co-occurring health conditions interact at individual and population levels, mutually amplifying disease burden and negatively impacting health (Tsai et al., 2017). For example, in cases of co-infection with tuberculosis (TB) and influenza, TB can exacerbate influenza infections. Influenza can then enhance bacterial lung disease, impair normal recovery mechanisms, and impair the immune system. Influenza can also cause latent TB to erupt. Together, they interact to significantly amplify their respective health burdens, which results in exponentially worse health and mortality outcomes (Singer & Mendenhall, 2022).

It is important to note here that while "disease interaction" and "disease clustering" are often used in the literature, syndemic theory applies to and encapsulates any health-related condition that can have significant impacts on an individual's health. As mentioned above, the first syndemic to be coined–the SAVA syndemic–includes interactions between violence and substance abuse and HIV/AIDS infection. While violence is not a disease, the impacts of violence can directly affect an individual's health and/or result in behavioral changes that significantly impact their health (Singer, 1996, 2009). Modern syndemic literature includes many health-related conditions that are not in themselves a disease but undoubtably affect health such

as experiences of water- and food-insecurity and syndemic interactions within the context of pregnancy (Singer, 2013; Workman & Ureksoy, 2017). Therefore, discussion of syndemic disease clustering or interaction is understood broadly and not limited only to "diseases".

The second key principle of syndemics is that when diseases/health-related conditions co-occur, biological interaction can often, but not always, happen (Singer & Clair, 2003). As such, co-occurrence does not automatically indicate interaction (Singer, 2009). Furthermore, diseases/health-related conditions can interact in diverse ways (see Chapter 2). Diseases and health-related conditions can share syndemic or counter-syndemic relationships, where the development of one condition offers some immunity or resilience to another, leading to positive health outcomes. For example, in a bioarchaeological context researchers have tried to determine whether tuberculosis and leprosy may be an important historical example of a counter-syndemic (e.g., Crespo et al., 2019; Donoghue et al., 2005). Proving that interaction between health-related conditions has occurred has proved to be the most challenging component for syndemic research (Bulled & Singer, 2025; Tsai, 2018)

The last core principle of syndemic theory - biocultural conditions that give rise to syndemic diseases - examines how overarching socio-political structures and forces create the environments responsible for disease clustering. Whether or not syndemic disease interaction occurs depends on both the biological capacity for disease interaction and the social and physical environments (Crespo et al., 2019; Mendenhall, 2012). Diseases and health-related conditions can therefore syndemically interact in one population and can co-occur without substantial interaction in another (Mendenhall, Newfield, et al., 2022). For example, the co-occurrence of musculoskeletal conditions and COVID-19 resulted in greater risks of COVID-19-related fatalities in lower-income countries, but not necessarily in higher-income countries. This has been tentatively linked with the fewer existing care services for individuals with musculoskeletal conditions in lower-income countries (Mendenhall, Kohrt, et al., 2022).

This last core principle of syndemic theory touches on biocultural models of health, which have become foundational in bioarchaeological research (Agarwal & Glencross, 2011; Cheverko et al., 2020). The first two core principles of syndemic theory (i.e., disease clustering and interaction) thus distinguish it and syndemic analytical models from other biocultural models of health in bioarchaeology and related fields. As Stephens (2008, p. 144) states, syndemic theory has helped illuminate "…the limitations of reductionist epidemiological paradigms that emphasize exposure-disease associations of self-contained, homogenous, or independent phenomena". It has been applied widely throughout medical disciplines, including medical anthropology, epidemiology, medical history, and, increasingly, bioarchaeology and its sister disciplines (Larsen & Crespo, 2022; Schug & Halcrow, 2022; Singer et al., 2017; van Schaik & DeWitte, 2020). Regardless of whether researchers seek to identify syndemics in past populations explicitly, the syndemic analytical model is an invaluable tool that can build upon current approaches. As an analytical tool, it broadens what variables researchers might consider significant. It underlines that to understand the complexities of health data fully - how it varies within and between populations, and what it reflects about lived experiences – researchers need

to account for the larger epidemiological landscapes in addition to social ones. To do otherwise is to have an incomplete picture.

Syndemic theory has gained increasing traction within bioarchaeology and related disciplines (see Chapter 2; Crespo, 2022, 2023; DeWitte et al., 2022; Dimka et al., 2022; Larsen & Crespo, 2022; Perry & Edwards, 2021; Perry & Gowland, 2022; Sawchuk et al., 2022; Schug & Halcrow, 2022b; van Doren, 2023; van Doren & Kelmelis, 2023; Zuckerman et al., 2022, 2023). Current research focuses on historic epidemics, such as the medieval outbreak of the Black Death and the 1918 influenza pandemic (e.g., DeWitte et al., 2022; Dimka et al., 2022; Larsen & Crespo, 2022; Schug & Halcrow, 2022b; van Doren & Kelmelis, 2023; van Schaik & DeWitte, 2020). This work exemplifies how the astounding mortality outcomes of past epidemics were often the result of interactions between diseases and health-related conditions already afflicting populations within specific biocultural environments, rather than the result of the fatality rate of a single disease. This has provided greater insight into how and why the impacts of past epidemics varied across time, regions, and specific populations. Syndemic approaches have also been applied to potential interactions between metabolic and infectious diseases, such as vitamin C and vitamin D deficiency, vitamin D deficiency and tuberculosis, and malaria and parasitic infections (e.g., Perry & Edwards, 2021; Perry & Gowland, 2022).

However, as Singer (2009) highlights, the operationalization of syndemic theory and disease model involves a foundational shift in how researchers think about health-related conditions. To date, the significance and relevance of syndemic theory and a syndemic analytical model have often been discussed in specific contexts (e.g., primarily historical epidemics). However, because analytical models are the foundational tools that researchers use to structure, organize, and build research, applying a syndemic analytical model has cascading, wide-reaching implications for bioarchaeological and related research beyond research on past epidemics. To date, this broader application of syndemic analytical models and its implications for bioarchaeological research has not yet been explicitly outlined.

1.2 DIET, NONSPECIFIC STRESS, AND MORTALITY RISK

Analyses of diet, nonspecific stress, and mortality risk are mainstays of bioarchaeological research (Katzenberg & Waters-Rist, 2018; Schrader, 2018; Sofaer, 2006). Within this context, nonspecific stress refers to those skeletal indicators of stress, such as periosteal new bone formations, that cannot be attributed to any one specific condition (Buikstra, 2019; Weston, 2018). These data have been used to gain insight into many questions around population health, living conditions, socio-historical environments and practices, as well as variation within and between populations across space and time. Diet, nonspecific stress, and mortality risk are also biologically and socially interconnected. Biologically, an individual's diet can lead to various health risks, such as cardiovascular and metabolic diseases, subsequently affecting their mortality risk (Kandel, 2019). When nutritional needs are unmet, malnutrition—defined here as any deficiency, excess, or imbalance in intake of nutrition encompassing both under- and over-

nutrition—can undermine the immune system, increasing the risk of becoming ill (Brown et al., 2020; Singer, 2009). In individuals who are already ill, malnutrition can be exacerbated by complications such as nausea, reduced appetite, diarrhea, and the heightened nutritional demands of the immune system. This chain of events can ultimately result in significantly poorer mortality outcomes (Scrimshaw, 2003; Singer, 2009). Diet, nonspecific stress, and mortality are also mediated and interrelated through social contexts. For example, social hierarchies and cultural norms shape dietary practices, exposure to stress, and mortality risk (Juengst, 2018; Klaus et al., 2017; Sofaer, 2006).

The interconnectedness of these variables at the biological level can further influence their expression in skeletal remains, in the form of dietary stable isotopes, nonspecific skeletal lesions, and age-at-death. In cases where stress or disease results in nutritional stress, it can initiate catabolic processes where an individual's nitrogen stores are recycled to make new proteins, resulting in increases to $\delta^{15}N$ values (Beaumont et al., 2018; Duska et al., 2007; Fuller et al., 2005). Mortality data is also critical for understanding nonspecific stress data. Osteoblastic nonspecific lesions (NSLs) are some of the most common skeletal pathologies that bioarchaeologists encounter (Buikstra, 2019). NSLs can indicate an array of processes due to heterogeneous frailty and selective mortality. When correlated with increases in mortality risk, NSLs can be indicative of frailty, defined here as lower resilience to stressors that results in increased mortality (DeWitte & Wood, 2008; Usher, 2000). Conversely, NSLs can indicate survivorship and resilience when linked to lower mortality risk. Additionally, individuals may become ill and die before NSLs can form, so the absence of NSLs can also reflect frailty or survivorship, depending on the relationship with mortality risk (DeWitte & Stojanowski, 2015; Wood et al., 1992). It is, therefore, critical to examine the relationship between nonspecific stress and mortality risk to understand what these nonspecific skeletal lesions indicate.

The relationship between these variables has been examined in bioarchaeological research. Following discrete approaches, the relationship between dietary stable isotope data or paleopathological data and mortality risk is most often examined to assess their impacts on health (e.g., Betsinger & DeWitte, 2017; DeWitte, 2014; DeWitte & Hughes-Morey, 2012; Baldoni et al., 2021; Marklein et al., 2016; Redfern et al., 2019; Reitsema et al., 2016; Yaussy et al., 2016). Research has also examined the relationship between dietary stable isotope values and the presence of nutritionally-linked diseases or stressors (e.g., Garland et al., 2018; Quintelier et al., 2014; Waters-Rist & Hoogland, 2018). As mentioned above, the application of a syndemic analytical model has primarily been within research examining historic epidemics rather than these broader topics of bioarchaeological analysis. As such, analyses of dietary stable isotopes, nonspecific stress, and mortality risk are typically not integrated. A syndemic model suggests that integrating analyses to account for their interrelationships can help build deeper and more dynamic insights into their patterning and variance within and between populations. This raises the question of how to do this effectively.

1.3 MULTIVARIATE AND MULTIVARIABLE ANALYSES

Multivariate and multivariable analyses allow for the simultaneous statistical analysis of three or more variables (Manly, 2004). Multivariate statistical analyses have multiple dependent, or outcome, variables (e.g., MANCOVA). Multivariable analyses have one dependent and multiple independent, or predictor, variables (e.g., Multiple Logistic Regression). These analyses can simultaneously test for the impact of the independent variable(s) on the dependent variable(s) and control for their influence on one another. As a result, variables that may not be statistically significant in bivariate analyses can prove significant in multivariate and multivariable analyses and vice versa (Manly, 2004). Because they consider independent variables simultaneously, they also better control for Type 1 errors (i.e., false positives) than bivariate analyses, which require a series of tests when an analysis has more than two variables (Manly, 2002).

Multivariate and multivariable analyses, though not as widely employed, have been used in diverse ways in bioarchaeology and related disciplines. They have been more commonly used in the development of methods, such as age-at-death estimation, and analyses of non-metric traits to study biological distance and migration (e.g., Baker & Pearson, 2006; Stull et al., 2014; Ullinger et al., 2005; von Cramon-Taubadel & Schroeder, 2016). They have been used to test how multiple factors, such as age and sex, influence the odds of dying during the Black Death, the processes of scalp removal, and differences in diet and health outcomes (e.g., DeWitte, 2024; Godde et al., 2020; Kesendell, 2018; Baldoni et al., 2021; Yaussy, 2019). They have also been used in regional paleoepidemiological research on intra- or inter-site comparisons (e.g., Vlok & Buckley, 2022) and to examine the variance in patterns and prevalence of degenerative joint diseases (e.g., Alonso-Llamazares et al., 2021).

Yaussy (2022) and Vlok & Buckley (2022) highlight the utility of multivariate and multivariable statistical methods for research on complex, interrelated data in paleoepidemiology, as well as intersectional bioarchaeological research, which examines how individuals' social identities (i.e., gender, race, class) can dynamically interact to affect lived experiences and health outcomes (Crenshaw, 1997) . One of the primary hurdles to using these statistical methods in bioarchaeological and related disciplines is that they require larger sample sizes. The rule of thumb for multivariate/variable analyses is that you need at least 10 data points per independent variable (Manly, 2004). The often small and fragmented state of many osteological samples in bioarchaeology and related fields makes this difficult, and accounts for their more limited use in research. However, where they can be applied, multivariable/variate statistical analyses are better suited for analyzing complex, interrelated health data.

1.4 ST. PETER'S CEMETERY

St. Peter's cemetery (10^{th}-16^{th} c. CE) is part of the St. Peter's Monastic complex in the modern village of Osor, Croatia. Osor is located on the island of Cres in the north-eastern

Adriatic. In late Antiquity (ca. 3rd-5th c. CE), Osor was the administrative center for the Cres-Lošinj archipelago and became the seat of a bishopric that would persist throughout the Middle Ages (Čaušević-Bully et al., 2014). The eastern Adriatic was a significant region for trade during this period, and Osor was located along important trade routes linking major entry points to western Europe, like Venice and the region of Istria, to the eastern Mediterranean (Čaušević-Bully et al., 2014; Ivetić, 2022).

Throughout the Middle Ages, Osor was impacted by many significant events. This includes outbreaks of plague in the 14th century CE and invasion and destruction by Genoese forces during the War of Chioggia, soon after (Miladinov, 2008; Protić, 2015). This region was also commonly afflicted with malaria and reported outbreaks in the 14th and 15th centuries CE decimated Osor's population (Novak et al., 2012; Protić, 2015). By the 15th century CE, the city began to lose its strategic importance as developments in sailing allowed for safer open sea navigation, diminishing the need for routes to follow the traditional safe harbors of the Adriatic islands (Mlacović, 2012; Protić, 2015).

St. Peter's Monastery was a Camaldolese Benedictine monastic complex established in the early 11th century CE (~1018 CE) by Osor's bishop and St. Peter's first abbot, Gaudentius (Čaušević-Bully et al., 2014, 2024). This monastery was one of a series of Benedictine monasteries established along the eastern Adriatic coast during this period in connection with the promotion of church reforms and a reassertion of papal authority across the Adriatic (Constable, 2017; Frankopan, 2021; Gioanni, 2013; Jurković, 2013). According to the Annales Camaldolese, the monastery peaked during the 11th to 12th centuries CE but fell into disrepair by the 1440s CE (Jurković et al., 2007; Miladinov, 2008). During its peak, St. Peter's Monastery was a center of ecclesiastical reforms in the area (Čaušević-Bully et al., 2014).

St. Peter's Monastery was excavated from 2006 to 2017 in a partnership between the International Centre for Research on Late Antiquity and the Middle Ages of Zagreb-Motovun (University of Zagreb), UMR 5594 ARTeHIS of the Centre Nationale de Recherche Scientifique (CNRS) (Dijon, France), Ecole française de Rome (Rome, Italy), and the Unité Mixte de Recherche (UMR) Chrono-environnement (Besançon, France). Excavations revealed the burials of 551 individuals. The burial ground at St. Peter's Monastery consisted of two cemeteries, the monastic and lay cemeteries, which extended across 5 burial sectors within and around St. Peter's church. These burials include a diverse sample of Osor's population, including St. Peter's monastic population and Osor's elite and non-elite secular (i.e., lay) population.

1.5 ORGANIZATION OF THIS THESIS

Each paper in this thesis contributes to answering my research questions outlined on pages 2-3. Chapter 2, "Building a Syndemic Bioarchaeology," presents the theoretical framework for this work, detailing how applying syndemic theory and a syndemic model shifts our analytical frameworks in bioarchaeology. This chapter discusses the implications for our conceptualization of health-related conditions/disease, research framing, research questions, methods, and how this

approach can be operationalized throughout bioarchaeological research. Following the ideas outlined in Chapter 2, Chapter 3 "Using Multivariable Statistical Analyses to Address Interrelated Data: An Examination of Diet, Nonspecific Stress and Age-at-Death in a Medieval Cemetery (Osor, Croatia)" provides a case study on how multivariable statistical analyses can be used to apply an integrative, syndemic analytical model in bioarchaeological research. This case study outlines the advantages and limitations of these methods and underlines how adopting this approach can significantly impact our results. This paper was prepared for submission to the *American Journal of Human Biology.* Finally, Chapter 4, "Intrapopulation Variation in St. Peter's Medieval (10^{th}-16^{th} centuries) Cemetery (Osor, Croatia): A Multivariable Analysis of Diet, Nonspecific Stress, and Mortality" puts the results from Chapter 3 in their socio-historical context and highlights what we can discern by applying a syndemic model as laid out in Chapter 2 and then operationalized in Chapter 3. This paper has been submitted for publication to *Bioarchaeology International*.

The methods section and supplemental data for Chapters 3 and 4 largely overlap. More detailed statistical methods are presented in Chapter 3 and more detailed methods for stable isotope and paleopathological analysis are presented in Chapter 4. Chapters 3 and 4 also share background information on the medieval city of Osor, Croatia, St. Peter's Monastery, and the Osor osteological sample.

CHAPTER 2: BUILDING A SYNDEMIC BIOARCHAEOLOGY

TITLE: BUILDING A SYNDEMIC BIOARCHAEOLOGY

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ABSTRACT

Calls for the use of syndemic theory as part of bioarchaeological and paleopathological research are becoming increasingly common. A syndemic model for studying health and disease emphasizes that diseases are not discrete entities; they are the product of interacting biological and social factors that result in exponentially worse health outcomes. While bioarchaeology has an established history of examining the intersection of social factors on past populations, studying disease interaction at a skeletal and population level will require shifting traditional research models. In modern syndemics research, researchers have cautioned that theorizing of syndemic interactions has outpaced the actual demonstration of evidence for interaction. This paper thus argues for the importance of ensuring that syndemics research in bioarchaeology is oriented around capturing evidence of interaction. We review the current extent of bioarchaeological research on syndemics, co-occurrence, and disease interaction to examine the scope of work to date. We then delineate how the syndemic models of disease shift traditional conceptualizations of disease, and what work could be done to promote syndemic research in bioarchaeology broadly. We suggest new areas of research that can be explored to further syndemic research, including how current bioarchaeological methods and analyses can be used for syndemic research on disease interaction.

2.1 INTRODUCTION

Bioarchaeology is the study of skeletal remains in past contexts through a wide variety of theoretical approaches and methods. Within bioarchaeology, paleopathology specifically focuses on the study of pathological conditions and diseases in the past. While analyses of stress, disease, and health-related conditions–their distribution, mortality outcomes, morbidity–are the focus of paleopathology, they are also foundational components across bioarchaeological research. Bioarchaeologists assess/analyze human skeletal remains to answer a variety of questions about past populations, including those concerning lived experiences, socio-cultural/environmental determinants of health, and their historical significance. Generally, this is done by diagnosing specific diseases or health-related conditions in individuals and populations, assessing factors that may have caused differences in frailty, age-at-death, and mortality, and/or comparing patterns and distributions of disease and other health-related data across contexts, usually in combination with historical and archaeological evidence that helps to interpret skeletal data.

Syndemic theory, which provides a theoretical framework for studying disease interaction and clustering driven by biosocial factors (Singer, 2009) has gained more attention within bioarchaeology, especially in light of the SARS-Cov-2 pandemic (see DeWitte & Wissler, 2022; Dimka et al., 2022; Larsen & Crespo, 2022). The application of syndemic theory within bioarchaeological work has generally focused on historical epidemics/pandemics (e.g., DeWitte, 2015; Sawchuk et al., 2022; van Doren & Sattenspiel, 2021), but recent work is increasingly demonstrating the value of a syndemic approach for bioarchaeological research on other health-related conditions, including infectious and metabolic diseases, more broadly (e.g., Crespo et al., 2019; Perry & Edwards, 2021; Perry & Gowland, 2022).

The growth of syndemics-based literature within bioarchaeology signals an interest in using syndemic theory to explore the interactive nature of disease and health-related conditions and investigate how social and environmental determinants of health interact to mutually reinforce each other. Using different theoretical frameworks to conceptualize disease and assess how it interacts with other factors shapes how research is designed and allows bioarchaeologists to more deeply understand the dynamic nature of disease and/or health-related conditions (Cheverko et al., 2020). The growing recognition of syndemics as a useful analytical framework highlights how bioarchaeologists can offer novel perspectives on both past diseases and syndemic research (Buikstra et al., 2022; Dimka et al., 2022; Perry & Edwards, 2021; Perry & Gowland, 2022; van Doren, 2023).

With the theoretical frameworks that are already used in bioarchaeology, such as the biocultural approach, the Developmental Origins of Health and Disease theory (DoHAD), embodiment, and life history approaches, bioarchaeologists are especially equipped to assess the convergence and interactions of socio-environmental factors that contributed to disease in the past, which is a crucial part of syndemic research. To date, discussions in bioarchaeology around syndemics have already covered the importance of investigating the social aspects of syndemics (e.g., Perry & Gowland, 2022; Sattenspiel & Herring, 2010; Zuckerman et al., 2022). However, as Tsai et al. (2017) underline, this does not make syndemic theory distinctive. Syndemic theory

centers the synergistic interaction between diseases and other health-related conditions and considers how this biological interaction affects health outcomes, lived experience, and disease burden. The biological interactions between diseases are as critical as the social interactions that influence the occurrence and spread of disease, and this is what sets syndemics apart from other biocultural frameworks (Mendenhall, Newfield, et al., 2022; Tsai et al., 2017).

Medical anthropologists emphasize the importance of capturing biological interaction in syndemic research since it defines syndemic theory (Mendenhall, Newfield, et al., 2022; Singer et al., 2020; Tsai, 2018). As bioarchaeology moves forward with the application of syndemic theory to study diseases in the past, it is important that research is intentionally structured to be able to capture and analyze disease interaction versus studying diseases and health-related conditions in isolation, as is more typical. The traditional Western, reductionist models of research that paleopathology and bioarchaeology are built upon are not always suited to capture disease interaction (Singer, 2009), and so it is important to consider how research design may need to shift to accommodate the use of syndemic theory and application of a syndemic model of disease/health-related conditions.

In this paper, we contribute to current discussions about syndemics in bioarchaeology, and incorporate current critiques from medical anthropologists on syndemic research, which emphasize the importance of capturing biological disease interaction (Mendenhall, Kohrt, et al., 2022; Tsai, 2018). We subsequently argue that centering disease interactions is key for building strong syndemic studies in the field and will require researchers to restructure research designs and questions that have traditionally been based on Western, reductionist frameworks. While some scholars take a broader view of what may constitute syndemic research (see Mendenhall, Newfield, et al., 2022), we follow the suggestion of Mendenhall et al. (2022) that syndemic research should be centered around disease interaction. As such, we define syndemic research as research that is explicitly framed around questions of disease interaction. This paper will: 1) Review the current work related to disease interaction in bioarchaeology and palaeopathology; 2) Outline how syndemic models of disease shift traditional conceptualizations of disease, and how this has important implications for various areas of bioarchaeological and paleopathological research; 3) Suggest new areas of research that can be explored to further syndemic research, including how current bioarchaeological methods and analyses can be used for syndemic research on disease interaction.

2.2 BACKGROUND

Singer (1994) coined the term “syndemic” to describe the phenomenon of two or more health conditions co-occurring within a population and synergistically interacting such that they result in exponentially worse health outcomes and cannot be treated separately. Three core concepts underlie the theory of syndemics: disease clustering, disease interaction/synergy, and causative social forces (Singer, 2009). The last component, the social and physical environments that give rise to syndemic diseases, examines how overarching socio-political structures and forces create social and physical environments that lead to disease clustering and synergistic interaction.

Situating results in a larger biocultural context is a familiar part of bioarchaeological research, and this aspect of syndemic research is already a foundational part of the biocultural approach used in bioarchaeology. While other biocultural theoretical frameworks can explain disease clustering and social/environmental determinants of health, syndemic theory is key for understanding the dynamics and outcomes of disease interaction (Mendenhall, Newfield, et al., 2022). When co-occurring diseases are syndemic, their disease development, distribution, and impact are inextricably intertwined (Singer, 2009). When this happens, we can not fully understand those diseases if we examine them separately. For example, the distribution and disproportionate mortality amongst Indigenous groups in Canada and New Zealand during the 1918 influenza pandemic cannot be explained without accounting for the interaction of influenza, tuberculosis, and other chronic respiratory diseases and social factors related to structural violence (e.g., limited access to healthcare and food) (Summers et al., 2018).

Research on disease in past contexts is modeled on the principles of the Western scientific disciplines they belong to, that is, principles of reduction and isolation (Shipley & Williams, 2019). The approach to knowledge in biomedical and clinical fields, which are often used to guide bioarchaeological research, is also primarily based upon these principles (Singer, 2009). Diseased organ systems are separated from the whole body, diseases are researched independently from one another, and disease-causing organisms are broken down into their constituent parts (Singer, 2009). However, research paradigms based on principles of separation are often unable to capture the dynamics of interaction between diseases when it does occur (Singer, 2009). In bioarchaeology, doing so can similarly skew our understanding of diseases in the past and fail to capture important nuances in how biocultural factors interacted with diseases on individual and population levels.

Syndemic theory is gaining increasing momentum within bioarchaeological research (see Crespo, 2022, 2023; Larsen & Crespo, 2022; Perry & Edwards, 2021; Perry & Gowland, 2022; Sawchuk et al., 2022; Schug & Halcrow, 2022b; Zuckerman et al., 2022, 2023). As bioarchaeological research on health-related conditions has traditionally been based upon those isolationist models not designed to capture the impact of disease interaction, it is important to critically examine how syndemic theory shifts conceptualizations of disease, and how bioarchaeological research questions and design may need to pivot to more fully explore disease interaction. Within modern syndemic research, medical anthropologists highlight issues with how disease interaction is identified and quantified (see Mendenhall, Kohrt, et al., 2022; Mendenhall, Newfield, et al., 2022; Tsai, 2018; Tsai et al., 2017). Tsai (2018) argues that theorizing on syndemics has outpaced actual empirical evidence of syndemic phenomena. A review by Singer, Bulled, and Ostarch (2020) determined that only 12% of 200 articles on syndemics met the full criteria for establishing a true syndemic. Mendenhall et al. (2022) further emphasize that it is difficult to argue for the presence of a syndemic without evidence of interaction, either at the individual or population level. As syndemic research gains more prominence in bioarchaeology, it is important that bioarchaeology is mindful of not reproducing these issues, and that research design can allow for the capture of interaction data. A syndemic approach can fundamentally change aspects of how bioarchaeologists think about disease co-occurrence, distribution, and morbidity in relation to disease interaction and raises questions that

have not been widely addressed in bioarchaeological research up to this point.

2.3 METHODS

To ensure that this review included the growing body of recent literature on co-occurrence, disease interaction, and syndemics, a scan of bioarchaeological literature was done. Google Scholar was used to capture published research across different formats (i.e., book chapters and articles) and journal publications. Search strings were constructed using relevant terms from previously researched literature on syndemics and co-occurrence. It was determined that incorporating the term "disease interaction" resulted in too many irrelevant hits and the few relevant hits it did immediately yield were captured in the final search strings. Two searches were done with the following search strings:

1. Co-occurrence: ((co-occurrence) OR (cooccurrence) OR (co-occur) OR (cooccur) OR (comorbid) OR (co-morbid)) AND ((bioarchaeology) OR (paleopathology))

2. Syndemics: ((syndemics) OR (syndemic) OR (syndemic theory)) AND ((bioarchaeology) OR (paleopathology))

The inclusion criteria consisted of publications specifically examining co-occurrence, the interaction between diseases or other health-related conditions, and those that explicitly used syndemic theory. Only research that included data was included as part of the final dataset; publications that provided an overview of syndemic research in bioarchaeology were excluded. Research that examined the prevalence of multiple health-related conditions or multiple nonspecific indicators of stress but did not record or report on whether those conditions co-occurred was also excluded. Due to the volume of results, the search was concluded once there were five consecutive pages of publications that did not fit the inclusion criteria.

Different fields within bioarchaeological research can use different language/terminology and thus may not be equally represented in this search; for example, stable isotope research generally did not turn up in the results although there is research that looks at the correlation/interaction between diet and pathological conditions using stable isotopes (e.g., Toyne & Turner, 2020). The search string used, however, was determined to yield the most relevant results and should still provide an accurate overview.

Gephi (v. 0.10.1) was used to create a network graphic that shows the results of the search. Research was classified into one of three categories. "Co-occurrence" included research that examined the co-occurrence, but not interaction, of two or more conditions either on a population or individual level. Research that examined the interaction between multiple diseases but did not explicitly identify their research as syndemic was categorized as "disease interaction". Lastly, research that explicitly referenced using syndemic theory and looked at disease interaction was grouped under the "syndemic research" category.

Individual nodes were labeled based on how the authors categorized their data/findings. For example, while some studies looking at bone fractures categorized their data as "Trauma", others specifically looked at "Violence", and so nodes were created for both. Additionally, some

studies looked at periosteal new bone formation (PNBF) or cribra orbitalia (CO) as nonspecific indicators of health or environment, so they were included under the label of "nonspecific disease". However, others examined PNBF or CO specifically as indicators of infectious disease or anemia respectively and were labeled as such.

When possible, each node was assigned a broad category of disease based on the categorizations from Buikstra (2019), which is then represented by the color of the node. The force atlas spatial layout algorithm was applied to the data, which places the most connected nodes at the center of the network. The largest nodes represent diseases/conditions that are most highly represented, and the connecting line thickness represents the number of articles that concern the two disease nodes that the line connects. When articles examine more than two diseases (e.g., nonspecific disease/trauma, nonspecific disease/infectious disease, and nonspecific disease/neoplasms), each interaction is represented as its own connection line.

2.4 CO-OCCURRENCE, DISEASE INTERACTION, AND SYNDEMICS IN BIOARCHAEOLOGY

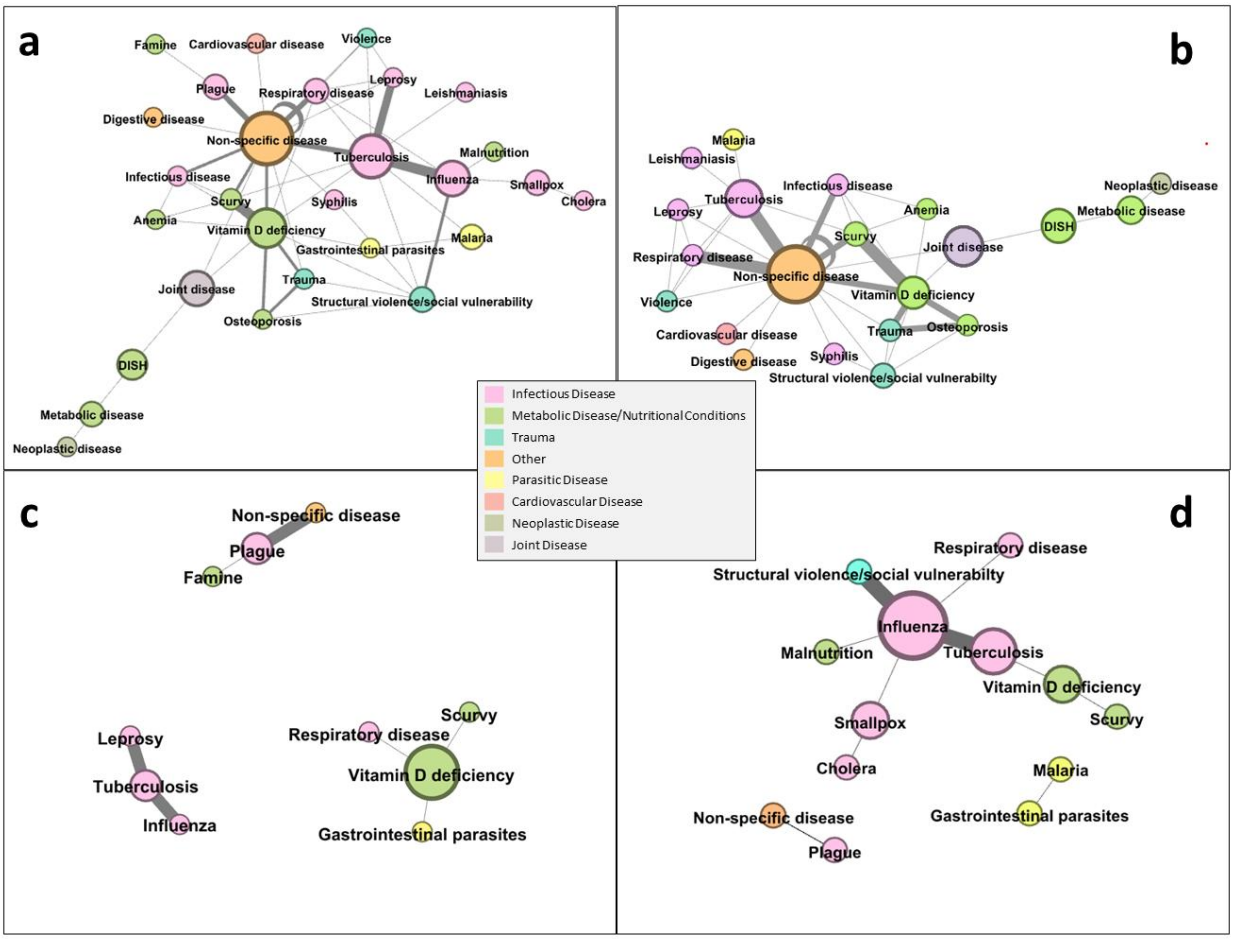

Figure 2.1: Network graph of extant examples of bioarchaeological research on disease co-occurrence and interaction. Larger circles indicate more papers published on that topic. The connecting lines indicate which two diseases or health-related conditions were examined in an article. The line thickness indicates how many articles examined the relationship between two diseases/health-related conditions. Figure a) Conditions represented across all articles in the literature review; b) Conditions represented in articles examining co-occurrence; c) Conditions represented in articles looking at interaction but did not reference syndemics; c) Conditions represented in articles specifically using syndemic theory.

Figure 2.1 provides a visual representation of the number of articles published (indicated by the size of the circle), the breadth of health-related conditions covered in the literature, and which health-related conditions/diseases are examined together (indicated by lines connecting circles together; see Supplemental File 1 for a full list of articles). Figure 2.1a presents all publications focused on either co-occurrence, disease interaction, or syndemic interaction. Figure 2.1b shows only articles examining co-occurrence, Figure 2.1c shows those concerned with disease interaction, and Figure 2.1d shows those that explicitly use syndemic theory. These different versions of the network map demonstrate the breadth of diseases and disease combinations that have been studied under each heading and highlight the lack of diseases that are studied in research focused on disease interaction and syndemics compared to co-occurrence.

While syndemics-oriented literature is becoming more prominent in bioarchaeology, the results of the scan in this study revealed a dearth of explicit syndemic research in bioarchaeology, supporting this assessment (see Figure 2.1d). While research around questions of co-occurrence, disease interaction, and syndemics is certainly growing, the overall results of the current study demonstrate that the breadth of diseases represented in relation to the diseases bioarchaeologists and paleopathologists can examine is relatively constrained and many are represented by a single publication.

Figure 2.1 demonstrates that infectious diseases currently dominate bioarchaeological research on co-occurrence, disease interaction, and syndemics. Infectious diseases are the most represented category of disease, and many are in the center of the networks, indicating their interconnectedness with other disease nodes. The infectious disease nodes also have the most crossover with other broad disease categories overall, with diseases such as TB representing a larger proportion of the literature as well as being connected to metabolic diseases, trauma, and parasitic diseases. Additionally, many of the thickest lines, and thus the most studied connections, are between infectious diseases with each other or infectious diseases and nonspecific diseases.

The nonspecific disease node is also notable. It is the largest node and has a high degree of crossover with other diseases, particularly for co-occurrence research (Figure 2.1b). In part, this is unsurprising, as nonspecific indicators of stress are some of the most commonly studied skeletal pathologies in bioarchaeology (Buikstra, 2019). Research in this category often looked at the co-occurrence of nonspecific stress/disease indicators to understand patterns of overall health in populations (e.g., Liebe-Harkort, 2012) or to explore the relationship of nonspecific pathologies with one another (e.g., DeWitte & Bekvalac, 2011).

The presence of research silos is also evident in Figure 2.1a-2.1d, regardless of whether co-occurrence, disease interaction, or syndemics was the focus of research. Infectious diseases and metabolic diseases primarily cluster with each other. The thinly connected/less-central nodes indicate future areas of research that could be expanded upon, especially for diseases that have known syndemic relationships with other health conditions, such as parasites and infectious diseases (e.g., Leishmaniasis and TB) (Singer & Bulled, 2012).

Figure 2.1c and 2.1d also shows the limited breadth of diseases that have been studied as part of work on disease interaction or syndemic interactions. Many diseases or conditions that can be examined in bioarchaeological contexts and have documented syndemic relationships in modern syndemic literature have only been studied to a limited degree. Vitamin D deficiency and TB are one example; in the network diagram, they are represented by a single article that looks at the co-occurrence of these conditions (e.g., Ives, 2018) although the connection and interaction between malnutrition, metabolic diseases, and infectious diseases is well established (Singer, 2009). While there are limitations to what health conditions bioarchaeologists and paleopathologists can study (see Section 2.6), the contextual nature of disease interaction means that whether diseases interact and how they interact will differ across populations, context, and time and thus represent many different research possibilities. Metabolic conditions that are nutritionally related are also particularly likely to co-occur, as individuals who are at risk for one

nutritional deficiency also tend to be at risk for others (Singer, 2009), but these relationships are also not highly represented in extant research. This represents an opportunity to build upon modern research and provide a past perspective.

When the network graph is shown by research type (Fig. 2.1b-2.1d), it is evident that the scope of articles looking at disease interaction (Fig. 2.1c) and syndemics (Fig. 2.1d) is more limited compared to those that examine co-occurrence (Fig. 2.1b). Many of the diseases in the overall network (Fig. 2.1a) are co-occurrence research (Fig. 2.1b); these studies represented 51% (n=19 articles) of the literature reviewed. Within the co-occurrence studies, 32% of those studies (n=6) were case studies on specific individuals. The majority of the connections are thin because they are represented by a single study, also reflecting the current disparate nature of research on co-occurrence. Comparing how co-occurrence manifests in a variety of settings and communities helps to confirm general trends in co-occurrence prevalence and assess how local factors contribute to disease clustering. However, this type of larger-scale comparative analysis cannot be done unless data is generated for a variety of contexts.

The disease interaction category consisted of a smaller pool of literature (n=12 publications, 32% of the total sample) with fewer diseases/conditions represented (Fig. 2.1c). Notably, research on the diagnosis of multiple diseases, or how co-occurrence/interaction may affect skeletal manifestations of disease (e.g., Schattmann et al., 2016) was rare. The syndemic research category was smaller still in terms of proportions (n = 8; 20% of the total sample), though more diseases were technically represented (i.e., 13 vs. 10 conditions for disease interaction; Figs. 2.1c and 2.1d). Research on disease interaction and syndemic research mainly focused on infectious diseases (particularly TB) or metabolic diseases. These observations are likely due to the relatively recent incorporation of syndemic theory in bioarchaeology.

A final trend in the literature not evident in the graphic was the limited geographic and temporal contexts represented in this body of literature. Most syndemic research to date has focused on the Second Plague Pandemic and/or the 1918 influenza pandemic, which could also be driving the focus on infectious disease in Figure 2.1d. While articles discussed the interaction of TB, influenza, and respiratory diseases (n=4), 75% (n=3) of these focused on the 1918 influenza pandemic in North America. Additionally, 27% (n=10/39) of all articles and 35% (n=6/20) of the studies in the disease interaction and syndemics category were done on samples from medieval and modern English populations. Other contexts were most often represented by a single study, which significantly limits how the presence and patterns of disease interaction across and within different populations can be examined. In part, the focus on the 1918 influenza pandemic and English samples could be due to the significant amount of historic and bioarchaeological literature focused on these contexts, which allows for improved analysis of potential disease interactions. However, these archaeological and historical data exist for other contexts as evidenced by the other syndemic research in the review (e.g., Crespo, 2022; Sawchuk et al., 2022; Zuckerman et al., 2022). Additionally, even in contexts with smaller sample sizes and more limited historical data, modern syndemics research combined with analysis of mortality and morbidity trends can shed light on potential synergistic interaction (see Section 6.0).

Bioarchaeological research on co-occurrence, disease interaction, and syndemics is growing. Nearly half (46%, n=17) of the articles included in the network graph were published in the past five years. This growing body of literature is promising, and this network demonstrates the many different avenues that research on disease interaction can take. Developing a body of syndemic research is important, but this research does not necessarily need to look the same. The articles represented in this review demonstrate the breadth of methods that can be used including incorporating archival resources (e.g., Herring & Sattenspiel, 2007; Noymer, 2009; Sattenspiel & Mamelund, 2012; Sawchuk et al., 2022; van Doren & Sattenspiel, 2021; Zuckerman et al., 2022, 2023), clinical data (e.g., van Schaik et al., 2014), examining associations between diseases and their relationship to mortality risk and paleodemography (Blondiaux et al., 2016; DeWitte & Wood, 2008), and interweaving historical, environmental, and existing bioarchaeological data (e.g., Crespo, 2022; Crespo et al., 2017; DeWitte & Bekvalac, 2011; DeWitte & Hughes-Morey, 2012b; DeWitte & Slavin, 2013; Ives, 2018; Perry & Edwards, 2021; Perry & Gowland, 2022; Schattmann et al., 2016) to explore the nature of a possible syndemic. At the same time, Figure 2.1 also demonstrates that there is room to expand on current syndemic-oriented research, particularly by generating data from new samples that allow for comparisons across different contexts, explicitly using a syndemic disease model to frame questions, and extending research on the co-occurrence of health conditions to also include disease interaction.

2.5 SYNDEMICS AND SHIFTING MODELS OF DISEASE

In this section, we briefly outline how syndemic theory and its central tenet of disease interaction impacts how disease is conceptualized and how we frame disease/health-related conditions in our research. Syndemic theory and a syndemic model of disease/health-related conditions shifts bioarchaeological conceptualizations of disease away from discrete to models to more integrative ones so that disease interaction becomes a pivotal variable for assessing the history of diseases, their effects on past populations, and how they reflect the lived experiences and socio-cultural/environmental contexts of past populations. Centering disease interaction means that our ability to assess co-occurrence becomes a key part of research, and changes how we approach the study of variables such as disease distribution and disease burden.

2.5.i Co-Occurrence

Before examining if and how health conditions have interacted, we must first be able to establish if diseases and/or other health-related conditions have co-occurred. One of the first steps to pursuing syndemic research in bioarchaeology is to first work towards establishing differential diagnosis frameworks for co-occurring conditions. In syndemic research, co-occurrence is a temporal term used to indicate the co-presence of diseases that do not assume a relationship between them (Singer, 2009). It is important to keep in mind that co-occurrence does not equate to disease interaction. Two conditions can co-occur without having a significant effect on disease risk, burden, or mortality outcomes (Singer, 2009). Additionally, two diseases or

health-related conditions can syndemically interact in one context but simply co-occur in another (Mendenhall, Newfield, et al., 2022). Improved diagnosis of co-occurrence is therefore a necessary step for syndemics research, but it must also go beyond simply identifying that co-occurrence is present within a context.

Paleopathology often uses the process of differential diagnosis, where various diseases are eliminated as the cause of skeletal lesions so that the final diagnosis can be as specific as possible (Mays, 2018). A syndemic model of disease highlights the importance of examining the presence and patterns of how co-occurrence manifests in bone across the skeleton, and how co-occurrence can be integrated into practices of differential diagnosis. For example, attempting to exclude too many diseases as part of the diagnosis and focusing on just one health issue might obscure cases of co-occurrence, as well as cases of disease interaction where the presence of multiple diseases altered the skeletal manifestations of disease (see Schattmann et al., 2016).

A syndemic model of disease, which recognizes that co-occurrence happens often, brings to the forefront these important questions and considerations around how to diagnose co-occurring disease and interpret bioarchaeological data. As the scan of the literature demonstrated (Figure 2.1) these areas of research have not been extensively studied. The paper by Schattman et al. (2016) was the only example where researchers examined the impact that co-occurring conditions can have on differential diagnosis, and it provides an example of how this might be done for other diseases and health-related conditions. For example, these authors used radiography, scanning electron microscopy, and macroscopic analysis to determine how the co-occurrence of vitamin D and vitamin C deficiency affected the expression of these conditions on skeletal remains.

2.5.ii Disease Interaction

When co-occurrence can be established, researchers can begin to ask questions that center around whether disease interaction occurred and can seek to identify potential pathways that drive this interaction (see more in Section 2.6). Even in cases where researchers are not explicitly setting out to examine co-occurrence, the potential for disease interaction should be considered when interpreting data in contexts where modern syndemic literature or other bioarchaeological research have established that interaction might occur (e.g., contexts of war, structural violence, and poverty, or between bacterial and viral infections, metabolic diseases, etc.).

A syndemic model also raises questions about *how* diseases have interacted with one another. Disease interaction can happen due to various biological processes (Table 2.1). As Crespo, White, and Roberts (2019) point out, the biological capacity for disease interaction to occur will also vary based on several biocultural factors. Therefore, the biological mechanisms of disease interaction also need to be considered as a contributing factor, as well as the environmental, structural, and social variables that lead to pathways of interaction. The context-specific nature of interaction further highlights the need to generate comparative data from a

wide variety of archaeological contexts. Research questions that center a syndemic understanding of disease interaction include how disease interaction occurs, why interaction may occur in some contexts but not others, what type of disease interaction is likely to have occurred, why specific populations or subgroups may be most vulnerable, and identification of the social and environmental variables that may be driving or affecting the interaction of disease.

Table 2.1: Examples of synergistic disease interactions.

Interaction*	**Interaction Mechanism**	**Example**
Alterations of the Physical Body	X promotes development of Y	Pulmonary tuberculosis or other lung infections result in residual cavities in the lobes of the lungs that aspergillus can then colonize (Singer, 2010)
Accelerated Virulence	X enhances virulence of Y	Herpes virus accelerates the pathogenesis of HIV/AIDS (Singer, 2009)
Enhanced Contagiousness	X enhances contagiousness of Y	Syphilis disrupts the epithelial barrier and causes genital-tract ulceration which supports the sexual transmission of HIV (Singer, 2009)
Mobility Support	X helps Y to access particular areas of the body	Amoebae act as a reservoir and protect Legionella bacteria allowing it to be aerosolized and inhaled by humans (Singer, 2010)
Iatrogenic Interactions	X undermines treatment of Y	HIV reduces the efficacy of measles vaccination

Alterations of Behavior	X alters behavior, causing the individual to act in a way that makes them more likely to develop Y	The experience of violence can result in more high-risk behaviors increasing the risk of substance abuse and HIV acquisition (Singer, 1996)
Gene Assortment	X causes genetic mutations or gene assortment in Y, changing it from one species/microorganism/strain to another	Gene mixing between different strains of HIV can lead to dual infections and the creation of treatment resistant strains (Singer, 2009)

* It is important to note that some combinations of diseases can interact in multiple ways.

2.5.iii Disease Distribution

Following a syndemic approach leads to subsequent questions on the dynamics of disease and other health-related conditions, such as disease distribution and burden. Applying a syndemic perspective to research on disease distribution will require that bioarchaeologists go beyond the history and pattern of just a single disease (Stephens, 2008). Instead, exploring trends in disease distribution throughout time requires knowledge of co-occurrence and interaction at regional, population, and subpopulation scales. Interactions with extant diseases in the population can help explain unexpected disease distributions, outcomes, emergence, or declines of particular diseases (DeWitte & Wissler, 2022; Newfield, 2022; Singer, 2009). Disease transmission and how different diseases are maintained in a population is not a straightforward process and is instead the result of many different interactions (i.e., between people, between animals, between diseases, between ecological factors, etc.) that occur within specific contexts (Vlok & Buckley, 2022). It is essential, therefore, that analyses of disease distribution trends try to account for this complexity and consider how the presence of multiple diseases plays a role in how these patterns and distributions develop.

2.5.iv Disease Burden and Lived Experience

A syndemic framework also offers a more layered understanding of how disease burden can affect the lived experience in the past since it focuses on the intersection between social factors, disease clustering, and disease synergism. Mendenhall (2012) calls this lived experience "syndemic suffering". A consideration of lived experience, or the intersection of identity and everyday actions and behaviors, offers greater access to the daily lives of past people (Brickley et

al., 2020, p. 198). Living with multiple diseases or health-related conditions, especially if those conditions are interacting, can significantly change the physiological and social experience of the disease. When these interactions are socially influenced conditions, such as differential access to nutrition or greater exposure to infectious diseases, the overall outcomes and lived experience of the conditions can be very different (Mendenhall, 2012). Accessing aspects of lived experience can be challenging in bioarchaeology (Brickley et al., 2020), so a consideration of syndemic suffering offers another avenue to explore this aspect of disease in the past by incorporating modern research on syndemic suffering into interpretations of lived experience.

The potential for interaction that can produce worse health outcomes means that analyzing the effect of many kinds of diseases on disease burden and mortality risk without considering co-occurrence and synergism may both under-estimate the overall disease burden on a population or overestimate/oversimplify the health effects that a single disease exerted on its own. We cannot comprehensively understand disease burden and its effect on lived experience through the lens of a single disease, health-related condition, or, as Battles and Gilmour (2022) argue, only during the period of active infection when disease interaction has occurred (see discussion below).

2.6 CRAFTING SYNDEMIC RESEARCH AND FUTURE DIRECTIONS

Purposeful use of theory is important throughout all steps of the research process. For syndemic theory, syndemic models of disease must be incorporated into how research is designed so that disease interaction can be empirically supported in bioarchaeological research. As Mendenhall , Kohrt, et al. (2022) reaffirm, without being able to identify interaction at the individual or population level, it is difficult to argue for the presence of a syndemic. Interdisciplinary research that breaks down bioarchaeological research silos, incorporates modern syndemic literature, and utilizes historical and environmental knowledge will be critical for analyzing the interaction, and for the wider use of syndemic theory within bioarchaeology.

As mentioned above, research on co-occurrence diagnosis and the skeletal manifestation of co-occurrence is important for being able to then look at disease interaction. Although co-occurrence has gained significantly more attention within bioarchaeology (Brickley et al., 2020; Buikstra et al., 2017; Mays, 2018), the current literature does not yet provide full coverage of the wide range of diseases that can co-occur, as evidenced from Figure 2.1b, or discuss how co-occurrence of these diseases can be diagnosed in skeletal remains. Not only will research on this subject help develop bioarchaeologists' ability to identify cases of co-occurring or clustering diseases (and thus potential disease interactions), but it will also provide insight into some of the physiological effects of disease interaction (Crespo, 2020; Mays, 2018). Using modern syndemic literature as a guide for what diseases can interact and the contexts they interact within paired with modern clinical research to examine how they manifest when co-occurring is one potential way forward (see Supplemental File 2 for a list of modern syndemic literature that may be useful for guiding bioarchaeological research). Samples for which a widespread prevalence of multiple diseases has been previously noted may also signal the possibility of co-occurrence that can be

investigated further. Additionally, comprehensively recording pathological alterations and using multi-method approaches (i.e., macroscopic analysis, radiographs, CT imaging, etc.) can also help decipher cases and patterns of co-occurrence.

As emphasized throughout this paper, capturing evidence of interaction for a wide variety of diseases and conditions is crucial to building a strong core of syndemic research in bioarchaeology. Evidence of interaction may include disproportionate mortality amongst individuals with multiple diseases, changes in survivorship during epidemics for individuals with pre-existing conditions, disproportionate rates of disease indicators amongst individuals from known epidemic/pandemic burial contexts, changes in patterns of disease distribution accompanied by evidence for the presence of multiple diseases, and historical accounts pointing to the co-presence of multiple circulating diseases. Other indicators that syndemic interaction is potentially affecting a past community and can be further investigated are excessive mortality or morbidity amongst certain demographics, evidence for co-occurrence on either an individual level or disease clustering on a population level, unexpected disease distribution patterns, historic or environmental accounts of large-scale events or societal changes, and unusual skeletal manifestations of disease.

Additionally, as Crespo, White, and Roberts (2019) discuss, disease interaction is unlikely to happen uniformly in all situations, and the capacity for an individual to develop cross-immunity and disease interaction is contingent upon the synergistic interaction of biological, ecological, and social factors. Mendenhall, Newfield, et al. (2022) further underline how contextually dependent disease comorbidity and interaction can be; diseases that are highly comorbid in one population may infrequently interact in another. These aspects of disease interaction then raise many interesting research questions for bioarchaeologists to pursue: Where is there evidence of co-occurrence, and is disease interaction occurring? Is it happening in some places but not others? What biocultural variables are driving interaction or a lack of interaction? How does the interaction of health-related conditions affect their skeletal manifestations? Comparisons of syndemic interaction across wide varieties of temporal or geographic contexts will be particularly interesting avenues of past health to explore.

While we may be able to say that individuals were afflicted with multiple conditions, limitations posed by skeletal data often make it difficult or impossible to determine whether those conditions truly co-occurred simultaneously. This can make it challenging to study co-occurrence and disease interaction at an individual level. However, it is not necessarily a prerequisite that individuals must have experienced diseases simultaneously for disease interaction to occur or for disease clustering to play a significant role in individual or population health. As Battles and Gilmour (2022) highlight in their work on using a ‘Survivor's lens’, not only can diseases affect individuals far beyond the period of active disease state, but those interactions can result in both social and biological vulnerabilities that create interaction between diseases even if they do not temporally co-occur. In the case of TB and polio, extended periods of inactivity can increase frailty, risk of fractures, and respiratory and cardiac complications (Battles & Gilmour, 2022). In the case of polio, visible physical changes as a result of the disease

also lead to social stigma that creates social vulnerabilities for survivors well after the course of the disease (Battles & Gilmour, 2022).

When the timeline of health conditions cannot be determined, researchers can still ask what conditions were clustering in a particular population, whether certain demographics were more affected by co-occurrence, why these trends developed, if there is evidence of interaction in certain contexts and not others, and if these patterns changed throughout time. DeWitte (2015) argues that incorporating research and data on aDNA and parasitic infectious diseases may be particularly useful avenues for exploring co-occurrence. This recommendation has not been followed extensively; to date, aDNA research on co-occurrence, in general, is limited, and published work has mainly identified infectious disease co-occurrence (e.g., Donoghue et al., 2005; Lalremruata et al., 2013).

Additionally, as the network analysis showed (Figure 2.1), interaction studies can also be centered on nonspecific stress indicators. While the lack of specificity poses limitations in terms of understanding the nature of interaction or whether nonspecific stress represents one or multiple health conditions, there are still multiple questions that can be explored. For example: 1) Is there clustering of certain indicators in specific groups?; 2) Does heightened mortality risk suggest either interaction or severe stress?; and 3) Is there a relationship between different skeletal indicators of nonspecific stress and/or other conditions?

Disease clustering and disease interaction can also be understood on a broader topical level by breaking down categories of skeletal disease data that are often examined separately. For example, degenerative diseases, infectious diseases, and violence can be interrelated and mutually informative in various social contexts, as discussed by Atwell (2022), who assessed the effects of structural violence on institutionalized women through examination of vitamin D deficiency, tuberculosis, syphilis, and hip fractures. Moreover, disease clustering and co-occurrence often take place within adverse social conditions, which can predispose individuals to many different kinds of health-related conditions (Singer, 2009) that are often siloed into different areas of bioarchaeological research. Breaking down research silos helps to better analyze co-occurrence across a wider variety of health-related conditions and opens avenues for bioarchaeologists to start examining cross-category patterns of co-occurrence and their socio-cultural and historical significance.

Additionally, examinations of disease co-occurrence or disease interaction do not need to be confined to samples where co-occurrence can be diagnosed individuals. When diseases cluster within a sample or community, there is potential for syndemic interaction at a wider level. Perry & Edwards (2021, p. 230) describe the population-based approach they used to understand multiple metabolic bone diseases in 19th century Jordan as "mirror[ing] the 'syndemic model'…". The commingled sample used in this research mostly precluded individual assessment of disease, although indicators of scurvy and rickets in some associated elements demonstrated the presence of co-occurrence. Perry & Edwards (2021) consequently infer co-occurrence and disease clustering at the population level through the overall rates of scurvy and rickets in this commingled sample.

Due to the pre-existing frameworks for researching a diverse spectrum of past health conditions, bioarchaeologists and paleopathologists are uniquely situated to bring a syndemic consideration of disease interaction to their research (Perry & Gowland, 2022). Research that expands upon the relationship between specific diseases over time can help to explain why patterns of disease distribution change, and why those patterns and trends may vary across different geographic contexts. Alternatively, assessing nonspecific disease indicators, and considering how stress and disease may have interacted across the life course, can also help to explore such trends. Answering these questions also necessitates an understanding of the biocultural determinants of disease both within and between populations. Bioarchaeologists can also expand studies that have been done on specific pandemics/epidemics in the past to examine how disease interaction may have been responsible for differential mortality risk, similar to research done on the 1918 influenza pandemic and the Second Pandemic of Plague (DeWitte, 2015; DeWitte & Wissler, 2022; van Doren & Sattenspiel, 2021). As part of exploring disease interaction, syndemic suffering and differential morbidity can also be considered. How might disease interaction fundamentally change an individual's or population's experience of disease? How does syndemic interaction result in syndemic suffering in modern-day case studies, and how might that have differed for past syndemics? What factors might be driving these differences or similarities?

2.7 TOOLS FOR SYNDEMIC RESEARCH

While more research on methods will be necessary to advance and build a more expansive syndemic literature moving forward, there are many currently available research methods that can help bioarchaeologists explore syndemics-oriented research questions. Current research provides examples of how challenges with identifying and examining co-occurrence can be addressed (Brickley et al., 2020; Milner & Boldsen, 2017; Schattmann et al., 2016). Additionally, paleoepidemiological methods of calculating the sensitivity and specificity of paleopathological indicators of disease for diagnosis may also provide another method to start untangling co-occurrence. For example, Pedersen et al. (2019) used reference collections with known instances of TB to create sensitivity and specificity estimates for paleopathological indicators of TB that could be applied to archaeological samples. Their research found that certain types of rib lesions occurred more often in their control sample with no recorded instances of TB and thus may be a more likely indicator of other nonspecific chronic pulmonary conditions that can co-occur with TB. This method may prove more broadly useful for helping to untangle skeletal manifestations of commonly co-occurring diseases.

Examining disease interaction means integrating more interrelated/dependent variables into analyses than is typically done with univariate and bivariate analyses. Consequently, analytical tools such as multivariable and multivariate statistical analysis will be important. These types of analytical methods allow for the exploration of the influence of multiple independent variables on a dependent variable or examinations of the relationships between multiple dependent variables and can help expand research concerning the interaction between health conditions and historical/contextual data. Vlok & Buckley (2022) recommend the use of multivariate statistics to assess how the interaction of different variables affected large-scale

disease transmission patterns, including looking at both morbidity and mortality. Mortality data and mortality risk analysis are also essential for investigating whether evidence of co-occurrence or disease clustering is associated with greater mortality risk compared to cases where just one disease or condition is present. For example, Sawchuck, Tripp, and Samakaroon (2022) found changes in life expectancy during a year with simultaneous cholera and smallpox epidemics in 19th century Gibraltar, indicating a synergistic interaction between the two diseases that contributed to excessive mortality. The use of other methods like Hazard Analysis can also be used to examine how different variables affect mortality risk for smaller-sized samples typical of bioarchaeological research (DeWitte et al., 2013; Redfern et al., 2019). While changes in mortality risk do not definitively prove syndemic interaction, they can provide important data to infer interaction when analyzed considering other bioarchaeological, historical, and environmental data.

Preservation can make the use of multivariate analyses difficult in some cases, as they are more sensitive to missing data than more common univariate and bivariate analyses. However, variables selected for analysis can be tailored based on the overall preservation of the skeletal sample, and certain lesions or indicators can be excluded if the element they are associated with is not highly represented. Moreover, Wissler et al.'s (2022a, 2022b) work provides guidance on how to manage missing data in bioarchaeological research so that multivariate analyses can still be used when preservation is a concern. Again, building syndemics-oriented research with the intention of using mortality data and multivariate analyses from the beginning is important, as it allows us to build research around the limitations of skeletal collections to ask syndemics-oriented questions about the effects of disease interaction.

Contextual data (i.e., historical or archaeological data), contemporary accounts, and demographic/census information are often crucial to bioarchaeological research on historical populations but can play an especially important role in the identification of both disease interaction and syndemics. By incorporating historical sources and keeping the potential for disease interaction in mind, researchers can explore the overlap and relationships between the diseases that are known to be present in a particular context, even if those conditions fall under vastly different broad categories of disease (e.g. parasitic infection, violence, social status, degenerative diseases, etc.). Large-scale population epidemiological trends in disease clustering can be investigated through the use of historical and archival sources (Herring & Sattenspiel, 2007; Sawchuk et al., 2022; Zuckerman et al., 2022) as can sociocultural variables and aspects of individual identity that may have contributed to disease interaction (e.g., living conditions, cultural practices, historical context/events, etc.). To understand the conditions under which disease interaction in the past developed on a wide variety of scales, incorporating available research on the socio-historical context of skeletal samples will be necessary. However, as no researcher can reasonably be expected to have the required expertise in all areas discussed above, inter-, intra-, and trans-disciplinary research provides one of the most immediate ways researchers can start pursuing in-depth syndemic research.

In addition to historical sources, if available, bioarchaeologists can also use modern syndemic research to guide their focus on diseases and to develop their research questions (see

Appendix B). Current syndemic and biomedical studies provide the groundwork for understanding which diseases are more likely to form relationships with one another, the conditions they tend to form under, how diseases interact, and how these interactions can vary by context. Additionally, literature on syndemic suffering in relation to social identity, intersectionality, and health can also be applied in past contexts to help inform research directions and questions.

Similarly, as others have already called for (i.e., Crespo, 2020; Crespo et al., 2017, 2019; Mays, 2018), greater engagement with the clinical literature on disease interaction and immunology will allow bioarchaeologists to better understand the multiple ways diseases can interact and the outcomes of these biological processes on overall health and/or on the skeleton. For example, DeWitte & Bekvalac (2011) found evidence of an interactive relationship between oral pathologies and systemic inflammatory responses. Work by Crespo et al. (2017) has also laid the groundwork for incorporating experiential immunology research within bioarchaeology by providing further evidence of how pathogen exposure can result in systemic inflammatory shifts that lead to more extreme inflammatory responses upon later pathogen exposure. Additionally, Crespo's (2020) skeletal inflammatory index (SINDEX) provides a method that allows researchers to think about systemic inflammatory reactions and how inflammatory immune responses can result in further synergistic cascades of inflammation. Indeed, this type of work will be critical for thinking about and working through how the presence of multiple diseases may affect the skeletal expression of disease and other health-related conditions. This work also illustrates why a syndemic approach to diagnosis is important.

2.8 CONCLUSION

Interest in syndemics in relation to past health and disease has grown over recent years, and researchers increasingly acknowledge the important role that syndemics may have had in past health crises (e.g., DeWitte, 2015; Dimka et al., 2022). The significant effect of disease clustering and interaction documented by syndemic research in modern populations further encourages us to analyze these relationships in past contexts and suggests that an understanding of syndemic interaction is not only useful but critical for understanding disease dynamics. To continue building a core of strong, syndemic-oriented bioarchaeological research, research must be structured to capture empirical evidence of interaction, in addition to data on the social, historical, and environmental contexts of past syndemics. This will require the contributions of multiple team members to capture all these different lines of evidence.

While there are challenges to identifying and studying historic syndemics, the approach brings to the forefront significant considerations and new research questions concerning the clustering and interaction of diseases and other health-related conditions/variables, regardless of whether a syndemic is identified. Framing research questions around syndemics and disease interaction provides an organizational pillar and facilitates meaningful comparisons across different contexts. A syndemic approach that emphasizes interaction encourages researchers to broaden the scope of information deemed relevant to understanding disease dynamics in the past,

break down categorical silos within the field, and allows for greater integration of interdisciplinary research into studies of health in the past.

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CHAPTER 3: USING MULTIVARIABLE STATISTICAL ANALYSES TO ADDRESS INTERRELATED DATA: AN EXAMINATION OF DIET, NONSPECIFIC STRESS, AND AGE-AT-DEATH IN A MEDIEVAL CEMETERY (OSOR, CROATIA)

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ABSTRACT

This study examines the analytical and interpretive implications of using multivariable versus bivariate statistical methods in bioarchaeological research, using a medieval osteological sample from Osor, Croatia (10^{th}–16^{th} c. CE). Traditional bivariate approaches, while useful for small or incomplete datasets, often fail to capture the complexity of interrelated health data. Rooted in Western scientific reductionism, bioarchaeology has historically emphasized discrete, siloed analyses. However, emerging integrative frameworks—such as syndemic theory—challenge this paradigm by emphasizing the interrelated and synergistic interactions among health conditions within specific sociocultural contexts. Applying this framework, this study demonstrates how multivariable analyses can be used to support interaction-focused research, offering deeper insights into the lived experiences of past populations. This case study compares the outcomes of bivariate and multivariable analyses of intra-population variation in interconnected dietary stable isotope, nonspecific stress, and age-at-death data, revealing that multivariable methods, particularly multiple logistic regression, can more effectively account for the interrelated nature of these data and support more insightful analyses of intra-population variation and their biocultural determinants. Despite challenges such as small sample sizes and preservation issues, syndemic research design and recent methodological advances enhance the feasibility of these approaches. This research contributes to a growing trend of integrative methodologies in bioarchaeological research and underscores the importance of aligning analytical strategies with theoretical frameworks. Ultimately, we argue that multivariable analyses can help capture the complexity of health, identity, and inequality in the past in ways that more commonly employed bivariate analyses often cannot.

3.1 INTRODUCTION

Analytical frameworks shape how we structure our research, including research questions, methods, and analyses, and govern what we infer from the data we produce (Geller, 2021; Stodder, 2012). The social sciences, including anthropology, are based on Western scientific reductionist approaches that categorize, isolate, and then analyze data discretely (Shipley & Williams, 2019). Bioarchaeology is a sub-discipline of biological anthropology, which has origins in the typological study of human variation in the 19th century and follows in the tradition of these discrete frameworks. This is reflected in how research is often siloed into specializations (e.g., dietary stable isotopes, migration, paleopathological studies, trauma studies, etc.), and research is structured with a focus on specific categories of data or conditions. Recent bioarchaeological research is adopting more integrative research models and theories (e.g., intersectionality) that highlight the complex, fundamentally interrelated, and interactive nature of the types of data we study (e.g., Mant et al., 2021; Schug & Halcrow, 2022; van Doren & Sattenspiel, 2021; van Schaik & DeWitte, 2020).

One such integrative model gaining attention in bioarchaeology is syndemic theory (e.g., DeWitte et al., 2022; Larsen & Crespo, 2022; Schug & Halcrow, 2022; van Schaik & DeWitte, 2020). Syndemic theory, developed by Merrill Singer in the 1990s, provides an explanatory model for why and how health-related conditions can cluster and interact to produce unique and exponentially worse health outcomes in specific sociocultural contexts (Singer, 1996, 2009). When this happens, the conditions' effects can no longer be understood in isolation. As such, syndemic theory emphasises how the interrelated and interactive nature of health-related conditions can have significant implications for the data that bioarchaeologists study. It expands existing biocultural models of health by highlighting the importance of considering the broader epidemiological landscapes within which individuals and populations exist (Singer, 2009). Research considering these interrelationships can enhance our understanding of the complexity, impact, and sociocultural determinants of health-related conditions, including intra- and inter-population variation.

Within bioarchaeology, there is a growing body of research orienting questions around interactions between health-related conditions and their impact on morbidity, disease distribution, and mortality outcomes (e.g., Crespo et al., 2017, 2019; DeWitte & Bekvalac, 2011; Ives, 2018; Perry & Gowland, 2022), how pre-existing health conditions influenced disease distribution, morbidity, and mortality trends in past epidemics (e.g., DeWitte, 2015; DeWitte et al., 2022; van Doren & Kelmelis, 2023; van Doren & Sattenspiel, 2021), and how intersecting identifies affected individuals' experiences and health outcomes (e.g., Yaussy, 2022; Zuckerman et al., 2022; Zuckerman et al., 2023). Diverse methods have been employed in these studies, including integrating bioarchaeological, clinical, and historical data, as well as epidemiological methods (e.g., crude death rates, survival rates) combined with bivariate and/or multivariable statistics. Multivariable statistics, defined further in the next section, are employed most often in research examining how intersecting identities impacted health outcomes (e.g., DeWitte & Bekvalac, 2011).

This type of integrative work requires research design to be structured to capture the complexities and interrelationships between health data. However, Singer (2009) argues that traditional, reductionist approaches are not the best suited for interaction-focused research. For instance, frequency-based or bivariate analyses that examine how a single health indicator—like nonspecific stress—varies by socio-cultural, temporal, or geographic factors cannot capture interactions with other health data. As bioarchaeology adopts more integrative approaches, it raises the question of which analytical methods can be leveraged to advance this research. In addition, as Vlok & Buckley (2022, p. 83) state, "… the challenge for bioarchaeologists is to unite these complexities [of disease] with the realities of archaeological data" including small sample sizes, poor preservation, and limits on what and how conditions manifest in skeletal remains.

Multivariable and multivariate statistics are a way researchers applying integrative analytical frameworks, like syndemic models of health-related conditions, can examine and account for interrelationships in their data. Vlok and Buckley (2022) highlight the utility of multivariate analyses in paleoepidemiological research, while Yaussy (2022) recommends these methods for advancing studies on the impact of intersecting identities on health outcomes. These statistical methods allow researchers to examine the simultaneous impact of multiple independent variables on a dependent variable(s) (Manly, 2004). As such, they are better suited for analyzing interconnected bioarchaeological data when they can be applied.

This research compares bivariate and multivariable analyses of intra-population variation in diet, nonspecific stress, and age-at-death using a medieval osteological sample from Osor, Croatia (10^{th}–16^{th} c. CE). It highlights how these methods yield different results and details the advantages and disadvantages of multivariable approaches, stressing their impact on analyses. Diet, nonspecific stress, and age-at-death were selected for analysis as they are commonly studied, interconnected data used in bioarchaeological research. The study operationalizes an integrative analytical framework that underlines the interrelated nature of health data rather than treat them as discrete through multivariable statistical approaches, thus emphasizing the importance of recognizing the interrelated nature of bioarchaeological data, how it can significantly affect analyses and interpretations, and how it can help advance further research incorporating more integrative analytical frameworks like syndemics. This work focuses on methodology; a separate publication covers the historical and archaeological context in detail (see Chapter 4, Propst et al. in review).

3.2 BIVARIATE, MULTIVARIABLE, AND MULTIVARIATE STATISTICAL ANALYSES

Bivariate statistical analyses (e.g., t-tests) examine the relationship between an independent (predictor) and dependent (outcome) variable. For example, t-tests can be used to detect significant differences in diet (e.g., $\delta^{13}C$ and $\delta^{15}N$ values) between subadults who died and those who survived into adulthood (e.g., Reitsema et al., 2016). Multivariate statistical analyses have multiple dependent and independent variables. For example, MANCOVA (Multivariable

Analysis of Covariance) can be used to examine the variation of $\delta^{13}C$ and $\delta^{15}N$ values (dependent variables) simultaneously based on age, sex, and archaeological site (independent variables) (e.g., Sotiriadou et al., 2022). Multivariable analyses (e.g., Multiple Logistic Regression) include one dependent and multiple independent variables. For example, dying from a condition (dependent variable) may be influenced by variables such as age, sex, and socio-economic class (independent variables).

A key advantage of multivariate statistical methods is their ability to assess the effects of multiple independent variables on one or more dependent variables simultaneously. As a result, variables that appear non-significant in bivariate analyses may prove significant in multivariate analyses, and vice versa. This is particularly beneficial in bioarchaeological research, where variables are often interrelated due to biological or biocultural factors (e.g., periosteal new bone formation and periodontitis, or sex, diet, and age-at-death). Multivariate methods also reduce the risk of Type I errors ("false" positives) more effectively than bivariate approaches, which require a series of individual tests (Manly, 2004). Additionally, they can incorporate interaction terms to explore how one variable (e.g., $\delta^{15}N$) influences a dependent variable (e.g., burial sector) depending on the values of another independent variable (e.g., age-at-death) (Menard, 2010). For a summary of useful multivariate techniques and their applications, see Yaussy (2022). A significant barrier to using multivariate/variable analyses in bioarchaeological research is the need for larger sample sizes and their sensitivity to missing data. Generally, a sample should have at least 10 cases for each independent variable, with a 20:1 ratio preferred (Menard, 2010). An entry/individual must have data for every variable in the final statistical analysis. This poses hurdles for bioarchaeological research, where skeletal samples are often small and fragmentary, and data are missing (see Wissler et al., 2022a, 2022b).

Multivariate/variable analyses, although less common than bivariate approaches, have often been used in bioarchaeology to develop age-at-death estimation techniques and analyses of biological distance (e.g., Baker & Pearson, 2006; Stull et al., 2014; Ullinger et al., 2005; von Cramon-Taubadel & Schroeder, 2016). They are increasingly applied to investigate how factors, such as age and sex, influence health outcomes or odds of dying during past epidemics (e.g., DeWitte, 2024; Godde et al., 2020; Yaussy, 2019), variation in dietary stable isotopes and patterns of degenerative joint disease (e.g., Alonso-Llamazares et al., 2021; Sotiriadou et al., 2022), the influence of diet and sex on age-at-death (e.g., Baldoni et al., 2021), the identification of reliable indicators of early life stress and sub-adult frailty (e.g., Wyatt et al., 2022), and regional-level paleoepidemiological studies (e.g., Steckel, 2005; Willis & Oxenham, 2013).

This study employs multivariable analyses in the form of multiple logistic regression, which has several advantages for research on skeletal samples and their often-complicated data. It does not assume a normal data distribution, homogeneity of variance, or a linear relationship between the dependent and independent variables. It also allows researchers to incorporate categorical and continuous data into their models and test interaction terms between independent variables.

3.3 DIET, NONSPECIFIC STRESS, AND AGE-AT-DEATH

Diet, nonspecific stress, and age-at-death are interconnected both biologically and socially. An individual's diet can result in varied health risks and stressors that influence mortality outcomes (Kandel, 2019). Social factors such as age- and sex-based status, poverty, and cultural norms further shape dietary practices and exposure to stress, influencing mortality risk (Juengst, 2018; Klaus et al., 2017; Sofaer, 2011). This relationship is observed in correlations between dietary stable isotopes and age-at-death (e.g., Baldoni et al., 2021; Redfern et al., 2019; Reitsema et al., 2016).

Research indicates osteological evidence can also reflect interactions between diet, stress, and age-at-death. When physical stress/disease causes nutritional stress, it initiates catabolic processes where an individual's nitrogen stores are recycled to make new proteins, increasing $\delta^{15}N$ values, with minimal change in $\delta^{13}C$ values (Fuller et al., 2005; Reitsema, 2013). Age-at-death data is also crucial for understanding nonspecific skeletal lesions (NSLs), such as periosteal new bone formations (PNBFs), which do not have a single cause and are thus considered indicators of nonspecific stress (Weston, 2018). PNBFs develop when the periosteum, a membrane containing osteogenic progenitor cells and osteoblasts that covers the outer surface of the bone, reacts to stimuli and forms new bone (Weston, 2011). This results in visually identifiable layers of new bone formation on top of the original cortical surface. Due to heterogeneous frailty and selective mortality, as outlined in the Osteological Paradox (Wood et al., 1992), both the presence and absence of NSLs can indicate frailty when correlated with higher mortality risk, or survivorship and resilience when correlated with lower mortality rates (DeWitte & Stojanowski, 2015). Frailty is defined here as lower resilience to stressors resulting in increased mortality risk, following DeWitte & Wood (2008) and Usher (2000). Additionally, DeWitte (2014) showed differing survival rates amongst individuals with no PNBFs, active PNBFs, and healed PNBFs, demonstrating connections between NSL characteristics (i.e., bone composition) and mortality outcomes.

These different data sources are commonly used in bioarchaeology to gain insight into a wide variety of questions about past peoples. In terms of their interrelationships, research typically focuses on the relationship between diet or paleopathological conditions and age-at-death (e.g., Betsinger & DeWitte, 2017; DeWitte, 2014; DeWitte & Hughes-Morey, 2012; Baldoni et al., 2021; Marklein et al., 2016; Redfern et al., 2019; Reitsema et al., 2016; Yaussy et al., 2016). Some studies have also explored the link between dietary isotopes and nutrition-related diseases (e.g., Garland et al., 2018; Quintelier et al., 2014; Waters-Rist & Hoogland, 2018). While multivariate/variable analyses are used in these studies, it is typically to explore the interactions/impact of factors like burial type or sex estimation (as a proxy for gender) (e.g., Baldoni et al., 2021; Yaussy et al., 2016), or method development (e.g., Marklein et al., 2016). Following traditional discrete frameworks, analyses of dietary isotopes, skeletal stress indicators, and mortality risk are usually not integrated. Integrative research models, such as syndemic models, suggest that integrating and analyzing the interrelationships of these data can yield new and dynamic insights into patterns of variance.

This article compares the results of bivariate and multivariable analyses of intra-population variation in $\delta^{13}C$ and $\delta^{15}N$ values, nonspecific skeletal lesions (NSLs), and age-at-death within the St. Peter's Monastery osteological sample from Osor, Croatia. St. Peter's Monastery and church included both a monastic and lay cemetery, featuring a mix of privileged and basic burials (Bully et al., 2024). We explore how the results and interpretations differ between the bivariate and multivariable analyses of diet, nonspecific stress, and age-at-death. Furthermore, we demonstrate that the multivariable analyses facilitate more complex examinations, which can help identify and control for covariance and interconnections within the data, as has been demonstrated in research on which nonspecific stress indicators reliably predict sub-adult frailty when co-morbidities can be controlled for using multivariable statistical analyses (e.g., Wyatt et al., 2022; Yaussy & DeWitte, 2018).

3.4 ST. PETER'S CEMETERY, OSOR

Osor is located on the island of Cres in the northern Adriatic Kvarner archipelago (Fig. 3.1). St. Peter's Monastery was a Benedictine monastic complex established in the early 11th c. CE (Čaušević-Bully et al., 2014; Bully et al., 2024). The monastery was excavated from 2006 to 2017 in partnership between the International Centre for Research on Late Antiquity and the Middle Ages of Zagreb-Motovun (University of Zagreb), UMR 5594 ARTeHIS of the Centre Nationale de Recherche Scientifique (CNRS) (Dijon, France), Ecole française de Rome (Rome, Italy), and the Unité Mixte de Recherche (UMR) Chrono-environnement (Besançon, France). The burial grounds included a monastic cemetery and lay cemetery that extended across five burial sectors (Fig. 3.2).

A total of 551 burials from the 10th-16th c. CE were excavated across the monastic and lay cemeteries. The monastic cemetery included a mausoleum and was identifiable archaeologically by its location south of the church (Sector 4), dominant male representation (i.e., 85% male; Table 3.2), and consistent use of masonry tombs for burials (Bully et al., 2024). The lay cemetery was distinguished by its location, burial types (e.g., shroud and coffin), overlapping burial orientations, burial goods, chronology, and the presence of women and children.

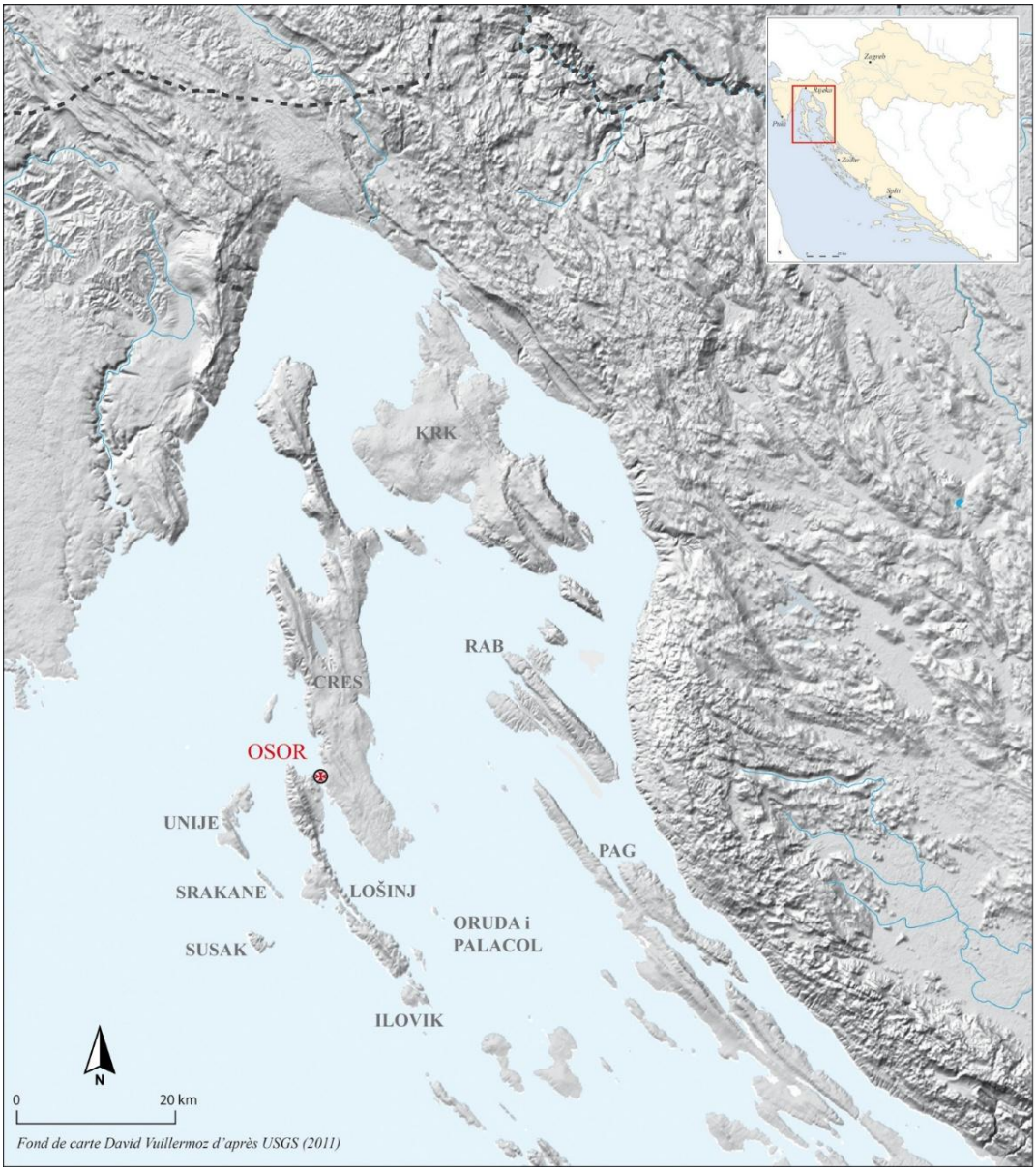

Figure 3.1: Map of Osor (from Čaušević-Bully et al., 2014). Reproduced with permission of M. Čaušević-Bully.

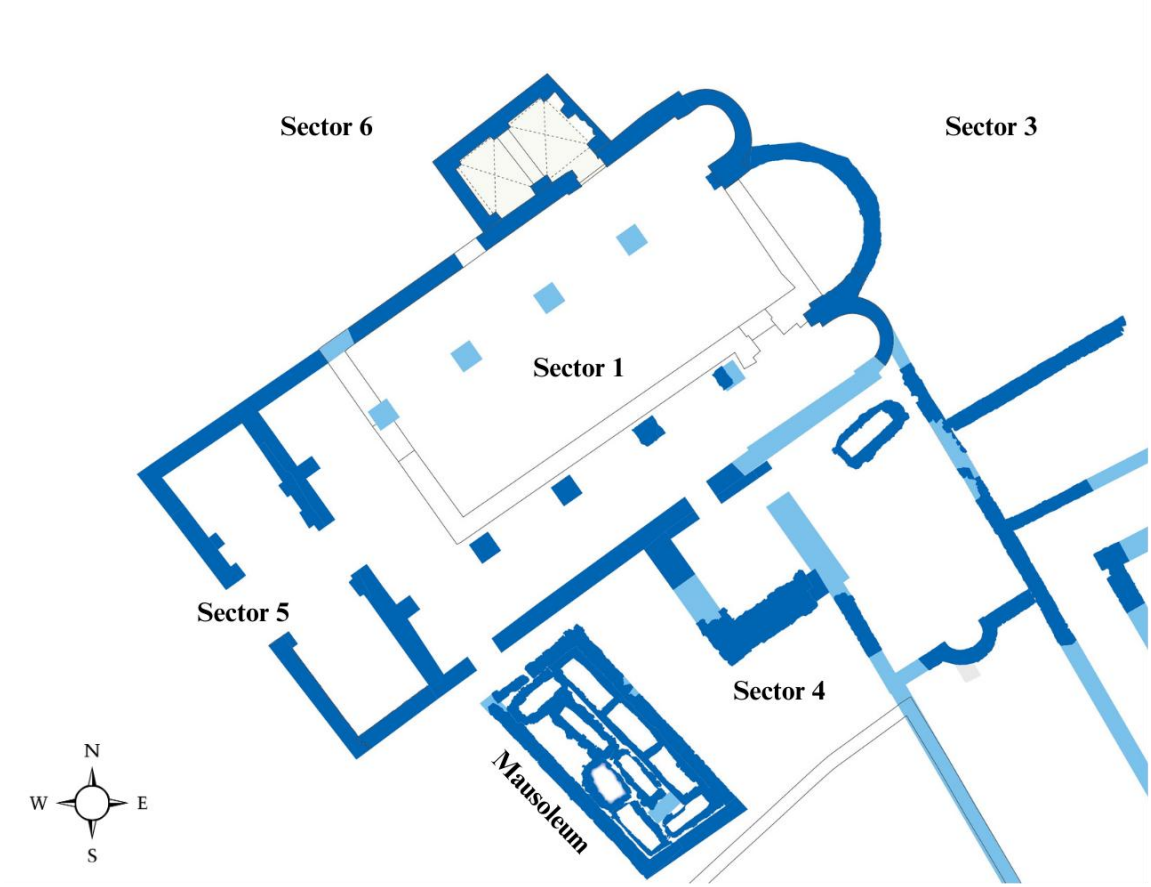

Figure 3.2: Plan of St. Peter's cemetery. Note that the monastic cemetery (including the mausoleum) and lay sector 4 are both in "Sector 4" with lay century burials located stratigraphically above the earlier monastic burials. Modified with permission of M. Čaušević-Bully

The monastic burials, located south of the church in Sector 4, date to the 10th-13th c. CE and are designated as "Sector 4M" in the analysis (i.e., Sector 4 Monastic). This cemetery was demolished and covered by lay burials during the 14th-15th c. CE after St. Peter's monastery no longer housed a monastic community (Marić et al., 2014; Velčić, 2024). The lay burials span five burial sectors: 1, 3, 4, 5, and 6 (Fig. 3.2; Table 3.1). While burial at St. Peter's monastery in itself suggests a degree of privilege for lay individuals, burials were classified as 'basic' or 'privileged' based on burial location, type (e.g., shrouds/coffins vs. stone tombs), and, in some cases, the presence of grave goods (Bully et al., 2024). Sectors 1 and 5 (13th-16th c. CE) are located within the church, a privileged burial location in medieval cemeteries, indicating these individuals were likely Osor's elite and are thus all considered privileged (Čaušević-Bully et al., 2017). Sector 3 has a mix of basic and privileged burials; its location behind St. Peter's apse and grave goods, like spurs, also suggest inclusion of Osor's local aristocracy (Čaušević-Bully et al., 2011). Sector 4 (14th-16th c. CE) is comprised of basic lay burials and is located stratigraphically above the earlier monastic cemetery. Sector 6 (12th-15th c. CE) features a mix of basic and privileged burial types (Bully et al., 2008).

Radiocarbon dating by Marić et al. (2014) reveal that some burials in the monastic cemetery predate St. Peter's monastery. However, burial phase reconstructions indicate that most burials, dating from the 11th c. CE onwards, were reserved for the monastic, male population (Bully et al., 2024). In Sector 3, the preponderance of male burials and 11th c. CE burials suggest that some individuals linked to the monastery may have also been buried there (Čaušević-Bully et al., 2014; Marić et al., 2010). Archaeological context, such as female and child burials, burial types, and burial goods, suggests most Sector 3 burials are likely those of lay individuals. This was still controlled for in the analysis to ensure possible admixture did not skew results (see below).

Table 3.1: Sample size, chronology, and location of St. Peter's burial sectors for the full (n=341) and multivariable (n=196) samples.

Sector	N (Full)	N (MV)	Chronology	Location	Burial Types
1	16	13	13th-16th c.	Church Nave	Privileged
3	55	28	11th-15th c.	East of Church	Mixed
4 (Lay)	59	26	15th-16th c.	South of Church	Basic
4M (Monastic)	125	78	10th-13th c.	South of Church	Monastic
5	32	16	13th-15th c.	Church Vestibule	Privileged
6	54	35	11th-15th c.	North of Church	Mixed
Total	341	196			

Osor's osteological sample was selected for this case study because it exemplifies a standard bioarchaeological sample with varied preservation and fragmented remains. Additionally, previous bioarchaeological research on European monastic communities and medieval populations in continental and southern coastal Croatia suggests that differences in diet, nonspecific stress, and age-at-death can be expected between monastic and lay populations and between high- and low-status individuals (DeWitte, 2024; DeWitte et al., 2013; Marklein et al., 2016; Mays, 1997; Novak, 2013; Novak et al., 2017; Šlaus, 2000; Šlaus et al., 2007).

3.5 MATERIALS AND METHODS

A sample of 341 individuals was analyzed for this study. Only adults and adolescents whose long bones had begun to fuse (i.e., ≥ 14 years) were included, as the relationship between diet, nonspecific stress, and age-at-death differs in sub-adults due to processes of weaning and growth. Of these 341 individuals, a sub-sample of 196 well-preserved individuals (i.e., at least ≥ 50% preservation of all skeletal elements analyzed were "present") was selected for multivariable analysis. This study focuses on statistical analyses, so a concise summary of the

non-statistical methods is provided here; more detailed methodology and quality control information are provided in the Supplemental File. Age-at-death was estimated using Transition Analysis 2 (TA2), and the maximum likelihood age estimates were used for statistical analysis (Boldsen et al., 2002). Timing of epiphyseal fusion by Cardoso (2008a, 2008b) was used to estimate the age of individuals with partial long bone fusion (Fig. 3.3). Sex was estimated using Buikstra & Ubelaker's (1994) criteria for os coxae and crania (Table 3.2).

Table 3.2: Sex estimation for the full (n=341) and multivariable (n=196) sample by burial sector.

Full Sample (n=341)									
Sector	**Female**		**Male**		**Ambiguous***		**Indeterminate***		**Total**
	N	%	N	%	N	%	N	%	N
1	8	50	7	44	0	0	1	6	16
3	9	16	39	71	6	11	1	2	55
4 (Lay)	12	20	35	59	2	3	10	17	59
4M (Monastic)	17	14	99	79	6	5	3	2	125
5	13	41	13	41	2	6	4	12	32
6	15	28	29	54	8	15	2	4	54
Total	74	22	222	65	24	7	21	6	341
Multivariable Sample (n=196)									
Sector	**Female**		**Male**		**Ambiguous**		**Indeterminate**		**Total**
	N	%	N	%	N	%	N	%	N
1	8	62	5	38	-	-	-	-	13
3	5	18	20	71	3	11	-	-	28
4 (Lay)	7	27	19	73	-	-	-	-	26
4M (Monastic)	9	12	66	85	3	3	-	-	78
5	6	38	9	56	1	6	-	-	16
6	12	34	18	51	5	14	-	-	35
Total	47	24	137	70	12	6	-	-	196

*Ambiguous individuals refer to those individuals who had scorable osteological features for sex estimation and were scored as “ambiguous”. Indeterminate individuals are those for whom scorable osteological features were not present, and sex could not be estimated. No “indeterminate” individuals exist for the multivariable sample, as any missing values were imputed.

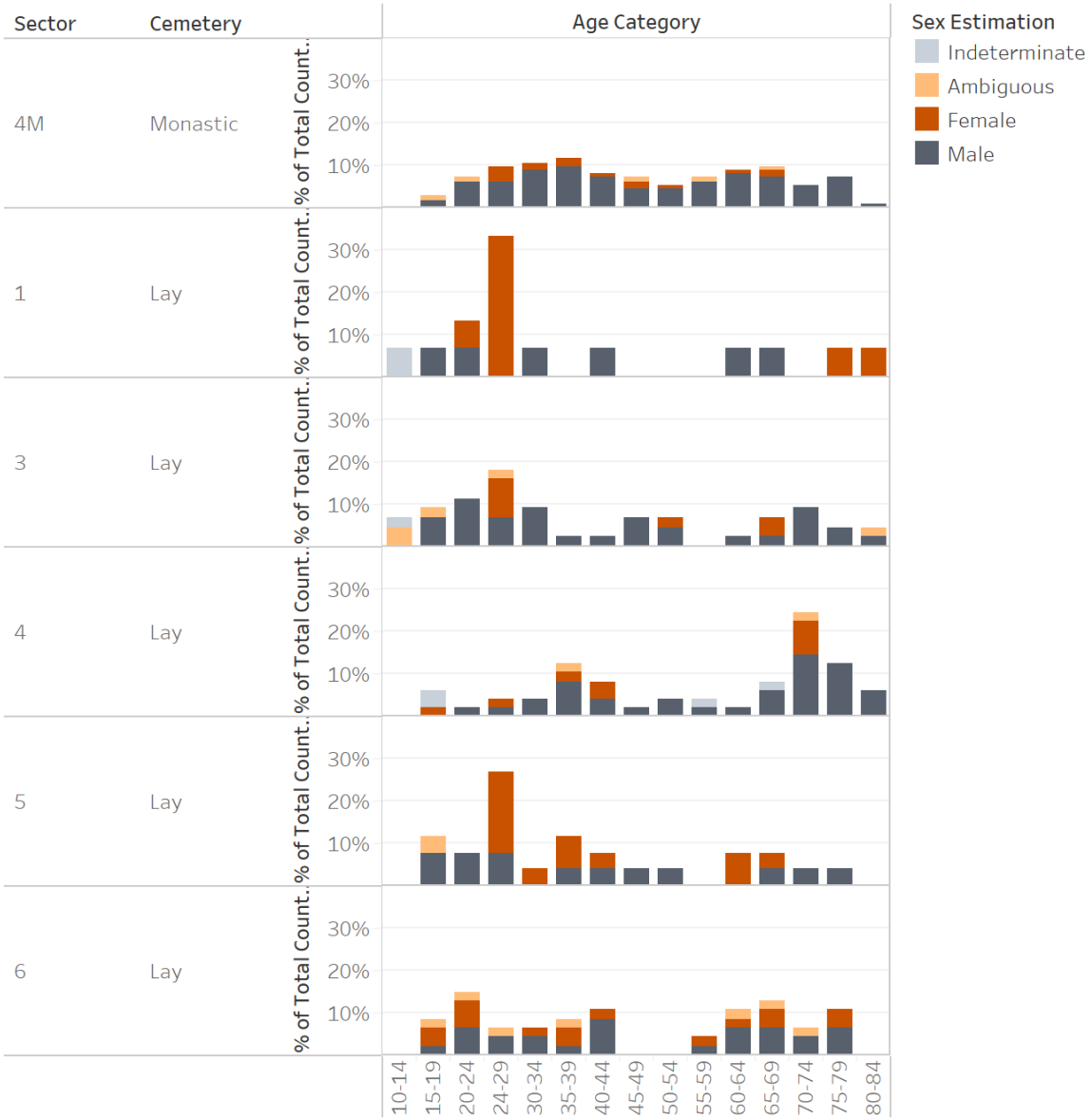

Figure 3.3: Age-at-death distribution by cemetery and burial sector for the full (n=341) sample.

A macroscopic paleopathological analysis recorded osteoblastic (i.e., new bone formation) nonspecific lesions (NSLs) on all long bones. Long bones were considered "present" if at least 50% was available for analysis. Clinical literature suggests that characteristics of nonspecific lesions (NSLs) can reflect the severity/intensity, duration, timing (i.e., active or remodeled), and distribution (i.e., systemic versus localized) of the processes that caused their formation (Bisseret et al., 2015; Ragsdale, 1993; Wenaden et al., 2005). These characteristics include:

- Bone composition (lamellar, woven, or mixed), which can reflect the timing or duration of a stressor;
- Lesion size, which may indicate the duration or severity of a stressor;
- And lesion distribution, which helps distinguish between localized and systemic involvement.

Accordingly, the analysis includes not only NSL presence or absence, but also NSL bone composition, the number of NSLs, the number of bones affected, and NSL size—measured by the maximum number of bone regions that an NSL spans (i.e., proximal/distal diaphysis and metaphysis, and proximal, middle, and distal shaft; n=7) per individual.

Stable isotope analysis on rib bone collagen was performed for 240 individuals. Results from 24 unpublished previously analyzed rib samples at the Institute for Anthropological Research (Zagreb, Croatia) were also included, for a total of 264 (Table S3.5). Collagen extraction followed the Longin (1971) and Chisholm et al. (1982) protocols. The prepared collagen samples were sent to the Ján Vizier lab, University of Ottawa, for stable isotope analysis. All $\delta^{15}N$ data are reported in ‰ (per mil) (AIR). All $\delta^{13}C$ data are reported in ‰ (VPDB). Repeated measures with internal standards (C-55 – L-glutamic acid) resulted in a standard error of 0.1‰ for both C and N. A subset (n=12) of the previously analyzed rib samples was prepared and rerun to assess consistency in stable isotope data between labs (Tables S3.2 and S3.3).

3.5.i Statistical Analyses

Unless otherwise indicated, all statistics were done with Jamovi, an open statistical software based on the R statistical language. Bivariate analyses, including chi-squared, t-tests, and analysis of variance (ANOVAs), were used to examine significant differences between monastic and lay cemeteries and burial sectors. Non-parametric tests were used when the data were not normally distributed. T-tests and ANOVAs assess differences in mean values, while chi-squared analysis evaluates the differences between expected and observed data.

Multivariable versions of these tests were performed using binary and multinomial logistic regression. Logistic regression is a statistical method for modeling the conditional or relative probability of belonging to one category versus another (i.e., monastic vs. lay) based on predictor (i.e., independent) variables (Menard, 2010). Binary logistic regression is used for a two-category dependent variable (cemetery type: monastic or lay), and multinomial logistic regression for a dependent variable with three or more categories (burial sector). Both models included $\delta^{13}C$, $\delta^{15}N$, age-at-death, NSL presence, NSL count, number of bones affected, NSL size, estimated sex, and two-way interactions among $\delta^{13}C$, $\delta^{15}N$, NSL variables, and age-at-death as predictors. Estimated sex was included to control for sex-based differences (Table 3.2).

Backward elimination was used where all variables of interest were entered into the regression model and those with p-values that did not meet the $\alpha = 0.10$ threshold were

sequentially removed until only those with significant p-values ≤ 0.10 remained (Menard, 2010). Therefore, all variables in the logistic regression models are significant. In multinomial logistic regression analyses, a reference category (i.e., burial sector) must be selected for the dependent variable to compare each successive burial sector against. This makes it more challenging to determine which predictor variables are significant in the overall model on the logistic regression results. So, an omnibus likelihood test, which assesses whether the predictors (independent variables) explain a statistically significant degree of variation in the overall model, was used to assess which predictors were significant.

An overall model test and Akaike's Information Criterion (AIC) were used to measure the model's fit (Menard, 2010). Interaction terms were only kept if they did not negatively impact the model's fit to ensure a parsimonious model. Continuous variables included different data scales (e.g., per mil ‰, years, counts) and were standardized using z-score transformations to facilitate interpretation. Individuals with significant outlying deviance residuals (i.e., z-score > 3.5) were filtered out for the binary logistic regression.

Variation Inflation Factor (VIF) and Tolerance statistics were used to check for non-multicollinearity in the regression analyses. Due to inherent correlations in the NSL data, only one to two paleopathological variables could be retained in the logistic regression analyses without violating assumptions of non-multicollinearity. Additionally, the paleopathological data had to be coded differently between the bivariate and multiple logistic regression analyses; in logistic regression, individuals without NSLs were assigned a value of "0" for NSL number, size, and bones affected, while in bivariate analyses, they were left blank.

Despite good preservation, some data were missing in the multivariable sample (n=196; Table 3.3). Missing values were imputed using IBM SPSS Statistics as recommended by Wissler et al. (2022a, 2022b). A MCAR (Missing Completely at Random) test confirmed that the missing data were randomly distributed (Table S3.4). Estimated-Maximization (EM) was then used to impute missing data.

Table 3.3: Percentages (%) of data missing for each independent variable. Variables not listed have no missing data.

Variable	Missing (%)
Age-at-Death	4.0
Sex Estimation	2.5
$\delta^{13}C$	1.0
$\delta^{15}N$	1.0

3.6 RESULTS

All graphs and the following averages are based on the full (n=341) sample. All data is presented in the Supplementary files. The average age-at-death was 47.2 (± 20.1) years, with peaks at ages 25-29 and 65-69 (Fig. 3.2; Table 3.4). The range of stable isotope results are: $\delta^{13}C$ = -19.9‰ to -17.3‰, $\delta^{15}N$ = 8.3‰ to 12.4‰ (mean -18.7 ± 0.4‰ and 10.7 ± 0.7‰, respectively). Table 3.5 and Figure 3.4 present the stable isotope data by group. Tables 3.6 and 3.7 present the paleopathological summary data. In the full sample, 53.4% (n=157/294) of observable individuals exhibited nonspecific lesions (NSLs), the majority of which were composed of lamellar bone (66.8%). Individuals in the full sample with NSLs had an average of 2.2 long bones affected, 2.8 NSLs, and the NSLs extended across 1.5 regions of the bone on average.

Table 3.4: Age-at-death summary data by cemetery (monastic vs. lay) and burial sector for the full (n=341) and the multivariable (n=196) samples.

	Full Sample				**Multivariable Sample**			
Group	**n**	**Mean (yrs)**	**Median (yrs)**	**SD**	**n**	**Mean (yrs)**	**Median (yrs)**	**SD**
All	293	47.2	43.7	20.1		47.4	44.9	18.9
Cemetery								
Monastic (4M)	114	47.6	45.3	17.7	78	47.8	45.8	16.0
Lay	179	46.8	42.0	21.6	118	47.3	44.4	20.0
Burial Sector								
1	15	39.0	27.4	22.8	13	38.5	27.4	21.9
3	43	41.9	31.9	22.4	28	44.2	36.8	21.5
4 (Lay)	49	56.6	65.7	20.1	26	53.3	52.3	19.8
5	26	39.3	35.0	17.9	16	43.4	39.3	19.3
6	46	47.9	44.0	20.6	35	50.3	46.1	19.7

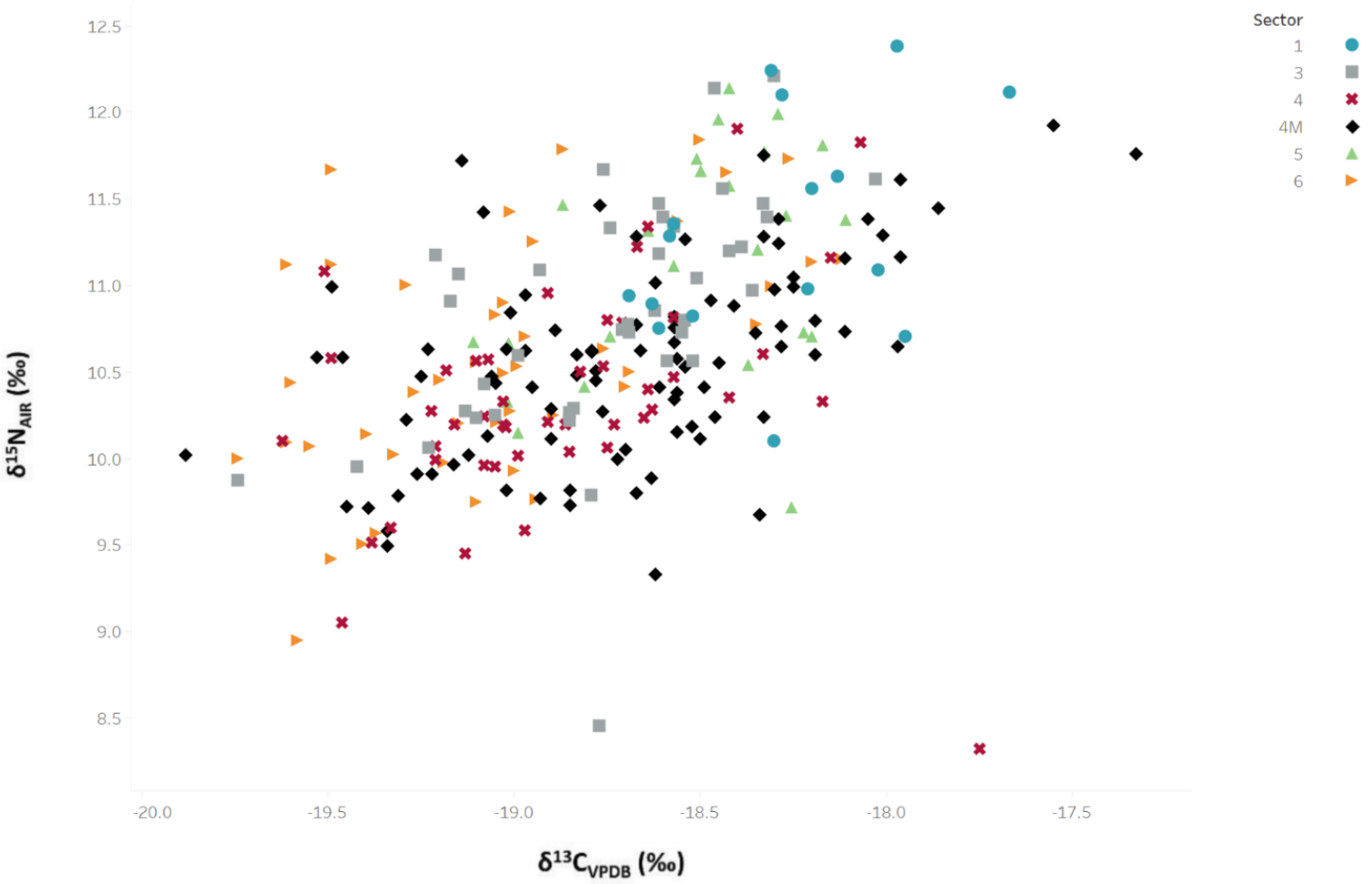

Figure 3.4: Stable isotope results differentiated by burial sector. Sector 4M refers to the monastic cemetery.

Table 3.5: Stable isotope summary data for the full (n=341) and the multivariable (n=196) sample.

	$\delta^{13}C$ (‰) VPDB				$\delta^{15}N$ (‰) AIR			
	Full Sample		**MV Sample**		**Full Sample**		**MV Sample**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All	-18.7	0.4	-18.7	0.4	10.7	0.7	10.7	0.7
Cemetery								
Monastic (4M)	-18.7	0.5	-18.7	0.5	10.6	0.6	10.6	0.6
Lay	-18.8	0.4	-18.7	0.4	10.7	0.7	10.8	0.7
Sector								
1	-18.3	0.3	-18.2	0.3	11.3	0.6	11.4	0.6
3	-18.7	0.3	-18.7	0.4	10.8	0.7	10.9	0.6
4 (Lay)	-18.9	0.4	-18.8	0.4	10.3	0.6	10.4	0.7
5	-18.5	0.3	-18.5	0.3	11.1	0.7	11.2	0.7
6	-19.0	0.4	-19.0	0.4	10.6	0.7	10.5	0.7

Table 3.6: Summary statistics for nonspecific lesion (NSL) prevalence and type for the full sample (n=341) and the multivariable sample (n=196)

Group	**NSL Prevalence (%)**		**NSL Bone Type (%)**					
			Lamellar		**Mixed**		**Woven**	
	Full Sample	MV Sample	Full Sample	MV Sample	Full Sample	MV Sample	Full Sample	MV Sample
All	53.4	64.8	66.8	68.5	29.9	29.1	3.2	2.4
Cemetery								
Monastic (4M)	66.3	74.4	61.2	65.6	32.8	31.0	6.0	3.4
Lay	46.6	58.5	71.1	71.0	27.8	27.5	1.1	1.4
Burial Sector								
1	75.0	69.2	58.3	66.7	41.7	33.3	-	-
3	40.0	46.4	72.2	76.9	27.8	23.1	-	-
4 (Lay)	38.9	65.4	71.4	64.7	23.8	29.4	4.8	5.9
5	44.4	37.5	83.3	83.3	16.7	16.7	-	-

6	52.9	68.6	70.4	70.8	29.6	29.2	-	-

Table 3.7: Summary data for nonspecific lesion characteristics for the full sample (n=341) and the multivariable sample (n=196)

Group	Mean NSL Number		Mean Bones Affected		Mean NSL Size	
	Full Sample	MV Sample	Full Sample	MV Sample	Full Sample	MV Sample
All	2.8	3.0	2.2	2.3	1.5	1.5
Cemetery						
Monastic (4M)	3.4	3.5	2.4	2.4	1.8	1.7
Lay	2.4	2.6	2.0	2.2	1.4	1.3
Sector						
1	2.3	2.7	2.2	2.4	1.5	1.7
3	2.3	2.5	1.8	2.0	1.4	1.2
4 (Lay)	3.4	3.9	2.6	2.9	1.4	1.4
5	1.9	2.2	1.9	2.2	1.7	1.5
6	2.0	2.0	1.8	1.8	1.2	1.2

Tables 3.2 and 3.4-3.7 show similar sample distributions and mean values between the multivariable sample (n=196) and the full sample (n=341), suggesting the multivariable sample is representative of the full sample. The most considerable difference was overall NSL prevalence (53.4% vs. 64.8%; Table 3.6). The full sample included more poorly preserved individuals with fewer skeletal elements present, and NSL prevalence is likely lower as a result.

3.6.i Bivariate vs. Multivariable Results

Table 3.8 presents the results of the bivariate analyses on the full (n=341) sample testing for differences between the cemeteries (monastic versus lay) and comparisons between the individual burial sectors (lay sectors 1, 3, 4, 5, and 6 and monastic sector 4M). Bivariate analyses were conducted on the multivariable sample (n=196) to identify any significant divergences that could indicate differences in sample composition influenced the multiple logistic regression results (Table 3.9).

Table 3.8: Results of bivariate analyses on the full sample (n=341). Statistically significant results are bolded and italicized.

Test	Dependent Variable	N*	Statistic	P	Mean Difference		Effect Size
Comparison of cemeteries (Monastic vs. Lay)							
Welch's T-Test	$\delta^{13}C$	264	1.52	0.129	0.10	Cohen's D	0.20
Welch's T-Test	***$\delta^{15}N$***	***264***	***-1.88***	***0.060***	***0.10***	***Cohen's D***	***-0.20***
Mann-Whitney U T-Test	Age-at-Death	293	9824	0.590	1.30	Rank Biserial Correlation	0.04
Chi-Square	***NSL Presence***	***294***	***10.30***	***0.001***		***Cramer's V***	***0.19***
Chi-Square	NSL Bone Composition	157	3.74	0.154		Cramer's V	0.15
Mann-Whitney U T-Test	***NSL Number***	***157***	***2332***	***0.005***	***1.02***	***Rank Biserial Correlation***	***0.23***
Mann-Whitney U T-Test	NSL Bones Affected	157	2643	0.166	0.22	Rank Biserial Correlation	0.12
Mann-Whitney U T-Test	***NSL Size***	***157***	***2351***	***0.006***	***0.36***	***Rank Biserial Correlation***	***0.22***
Comparison of burial sectors (Sectors 1, 3, 4, 4M, 5, and 6)							
One-way ANOVA	***$\delta^{13}C$***	***264***	***14.61***	***< 0.001***	***-***	***-***	***-***
One-way ANOVA	***$\delta^{15}N$***	***264***	***8.94***	***< 0.001***	***-***	***-***	***-***
Kruskal Wallis ANOVA	***Age-at-Death***	***293***	***22.20***	***< 0.001***		***Eta Squared***	***0.08***
Chi-Squared	***NSL Prevalence***	***294***	***18.50***	***0.002***	***-***	***Cramer's V***	***0.25***

Chi-Square	NSL Bone Composition	157	6.86	0.738	-	Cramer's V	0.15
Kruskal Wallis ANOVA	***NSL Number***	***157***	***11.10***	***0.049***	***-***	***Eta Squared***	***0.07***
Kruskal Wallis ANOVA	NSL Bones Affected	157	5.88	0.318	-	Eta Squared	0.04
Kruskal Wallis ANOVA	NSL Size	157	10.66	0.059	-	Eta Squared	0.70

* Because of variable preservation, stable isotope data, paleopathology, and age-at-death could not be assessed for every individual; 'N' values reflect the number of individuals observable for each dataset.

Table 3.9: Results of bivariate analyses on the multivariable sample (n=196). Statistically significant results are bolded and italicized.

Test	Dependent Variable	N	Statistic	p	Mean Difference		Effect Size
Comparison of cemeteries (Monastic vs. Lay)							
Welch's T-Test	$\delta^{13}C$	196	0.91	0.365	0.1	Cohen's D	0.13
Welch's T-Test	***$\delta^{15}N$***	***196***	***-2.18***	***0.03***	***0.1***	***Cohen's D***	***-0.31***
Mann-Whitney U	Age-at-Death	196	4451	0.70	.52	Rank Biserial Correlation	0.03
Chi-Square	***NSL Prevalence***	***196***	***5.19***	***0.023***	***-***	***Cramer's V***	***0.16***
Chi-Square	NSL Bone Composition	127	3.48	0.968	-	Cramer's V	0.08
Mann-Whitney U	NSL Number	127	1680	0.111	0.88	Rank Biserial Correlation	0.16
Mann-Whitney U	NSL Bones Affected	127	1873	0.521	0.26	Rank Biserial Correlation	0.06

Mann-Whitney U	***NSL Size***	***127***	***1481***	***0.003***	***0.41***	***Rank Biserial Correlation***	***0.26***
Comparison of Burial Sectors (Sectors 1, 3, 4, 4M, 5, and 6)							
One-way ANOVA	***$\delta^{13}C$***	***196***	***11.88***	***< 0.001***	***-***	***-***	***-***
One-way ANOVA	***$\delta^{15}N$***	***196***	***8.45***	***< 0.001***	***-***	***-***	***-***
Kruskal Wallis ANOVA	Age-at-Death	196	8.77	0.119		Eta Squared	0.04
Chi-Squared	***NSL Presence***	***196***	***12.80***	***0.025***	***-***	***Cramer's V***	***0.26***
Chi-Square	NSL Bone Composition	127	3.48	0.968	-	Cramer's V	0.12
Kruskal Wallis ANOVA	NSL Number	127	9.66	0.085	-	Eta Squared	0.08
Kruskal Wallis ANOVA	NSL Bones Affected	127	6.68	0.246	-	Eta Squared	0.05
Kruskal Wallis ANOVA	***NSL Size***	***127***	***11.99***	***0.035***	***-***	***Eta Squared***	***0.09***

Table 3.10 presents the binary logistic regression results comparing the monastic and lay cemeteries. Because backwards elimination was used, only significant variables are included in the final models; those not represented were not significant. The binary logistic regression model is statistically significant compared to the null model ($\chi^2 = 69.1$, $p < 0.001$), indicating that the independent variables better predict whether an individual belonged to the monastic or lay cemeteries than no predictors. The McFadden's R2 of 0.27 suggests a well-fitting model that explains 27% of the variance in the data, a substantial improvement over the null model with no predictors (McFadden R^2 values: < 0.1 = weak, 0.2–0.4 = good, > 0.4 = excellent; McFadden, 1973). Two individuals exhibited significant outlying residuals for predicted versus observed probability and were excluded to enhance the model's fit. Excluding Sector 3 burials did not alter the results, indicating that the possible inclusion of monastic individuals in this sector does not affect outcomes.

Table 3.11 presents the multinomial logistic regression results comparing the individual burial sectors. The multinomial logistic regression model was statistically significant compared to the null model ($\chi2 = 148$, $p = < 0.001$; Table 3.11). The McFadden's R2 was 0.25, suggesting a

well-fitting model that explains 25% of the variance in the data compared to the null model (McFadden, 1973). Due to small sample sizes in Sectors 1 (n=13) and 5 (n=16), these privileged burials (13th–16th c. CE) were combined into a single group (Sector 1/5) to improve statistical power in this analysis. The summary data suggest that Sectors 1 and 5 were the most unique, so they were used as the reference sector against which the other burial sectors were compared (i.e., Sector 1/5). Table 3.12 presents the results of the omnibus likelihood test, which shows which predictors were significant in the overall multinomial logistic regression model.

Table 3.10: Results of the binary multiple logistic regression. *

				Overall Model Test		
Model	**Deviance**	**AIC**	**R^2McF**	**χ^2**	**df**	**p**
1	191	209	0.266	69.1	8	< .001

					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**p***	**Odds Ratio**	**Lower**	**Upper**
Intercept	-0.12	0.21	0.556	0.89	0.59	1.33
Age-at-Death	0.47	0.20	0.019	1.60	1.08	2.36
$\delta^{15}N$	1.18	0.26	< .001	3.24	1.94	5.42
$\delta^{13}C$	-0.61	0.22	0.006	0.54	0.35	0.84
Sex Estimation**						
Ambiguous – Male	2.05	0.89	0.021	7.77	1.36	44.17
Female – Male	2.32	0.54	< .001	10.14	3.49	29.43
NSL Size	-0.54	0.20	0.007	0.58	0.39	0.86
$\delta^{15}N$ ✻ NSL Number***	-1.55	0.40	< .001	0.21	0.10	0.47
NSL Size ✻ $\delta^{15}N$	1.21	0.40	0.002	3.37	1.54	7.35

Note: Estimates represent the log odds of "Cemetery = 1" vs. "Cemetery = 0"

* Significance threshold was set at $\alpha = 0.10$

** For sex estimation, males were the reference category against which females and ambiguous individuals were compared.

*** Interaction terms are indicated by "✻"

Table 3.11: Results of the multinomial multiple logistic regression analysis.

Model	Deviance	AIC	R^2McF	Overall Model Test		
				χ^2	df	p
1	447	519	0.25	148	32	< .001

Multinomial Logistic Regression Model Coefficients						95% Confidence Interval	
Burial Sector*	Predictor**	Estimate	SE	p	Odds ratio	Lower	Upper
3 Basic and privileged lay burials (11th-15th c. CE)	Intercept	1.96	0.73	0.008	7.07	1.68	29.76
	Age-at-Death	-0.14	0.41	0.726	0.86	0.39	1.94
	$\delta^{13}C$	-1.02	0.45	0.024	0.36	0.15	0.87
	$\delta^{15}N$	-1.08	0.58	0.061	0.34	0.11	1.05
	Sex Estimation:						
	Ambiguous v Male	0.71	1.49	0.636	2.03	0.11	37.96
	Female v Male	-3.47	1.01	< .001	0.03	0.00	0.22
	NSL Size	-0.40	0.39	0.295	0.67	0.31	1.42
	Age-at-Death ✻ $\delta^{15}N$	-0.23	0.51	0.648	0.79	0.29	2.15
	Age-at-Death ✻ $\delta^{13}C$	0.60	0.45	0.184	1.83	0.75	4.47
4 Basic lay burials (14th-16th c. CE)	Intercept	2.06	0.72	0.004	7.87	1.90	32.57
	Age-at-Death	0.15	0.40	0.700	1.17	0.53	2.55
	$\delta^{13}C$	-0.14	0.45	0.749	0.86	0.36	2.10
	$\delta^{15}N$	-2.42	0.59	< .001	0.09	0.03	0.28
	Sex Estimation:						
	Ambiguous v Male	-0.30	1.63	0.854	0.74	0.03	18.06
	Female v Male	-3.25	0.97	< .001	0.039	0.00	0.26
	NSL Size	0.28	0.35	0.423	1.32	0.66	2.64
	Age-at-Death ✻ $\delta^{15}N$	-1.55	0.53	0.003	0.21	0.07	0.60
	Age-at-Death ✻ $\delta^{13}C$	1.30	0.45	0.004	3.66	1.52	8.83
6 Basic and privileged lay burials	Intercept	1.80	0.75	0.016	6.06	1.40	26.24
	Age-at-Death	0.50	0.40	0.219	1.64	0.74	3.63
	$\delta^{13}C$	-1.64	0.49	< .001	0.19	0.07	0.50
	$\delta^{15}N$	-1.44	0.60	0.016	0.24	0.07	0.77
	Sex Estimation:						

(12th-15th c. CE)	Ambiguous v Male	1.54	1.49	0.301	4.67	0.25	86.61
	Female v Male	-2.87	0.97	0.003	0.06	0.01	0.38
	NSL Size	0.15	0.37	0.682	1.16	0.56	2.43
	Age-at-Death ✻ $\delta^{15}N$	-1.08	0.52	0.038	0.34	0.12	0.94
	Age-at-Death ✻ $\delta^{13}C$	1.39	0.47	0.003	4.01	1.59	10.14
4M Monastic burials (10th-13th c. CE)	Intercept	3.42	0.69	< .001	30.58	7.92	118.00
	Age-at-Death	-0.26	0.38	0.499	0.77	0.37	1.62
	$\delta^{13}C$	-0.23	0.41	0.574	0.79	0.35	1.77
	$\delta^{15}N$	-2.75	0.57	< .001	0.06	0.02	0.19
	Sex Estimation:						
	Ambiguous v Male	-1.18	1.46	0.419	0.31	0.02	5.36
	Female v Male	-4.58	0.94	< .001	0.01	0.00	0.06
	NSL Size	0.53	0.32	0.092	1.70	0.92	3.16
	Age-at-Death ✻ $\delta^{15}N$	-0.95	0.50	0.057	0.39	0.15	1.03
	Age-at-Death ✻ $\delta^{13}C$	0.88	0.41	0.030	2.42	1.09	5.38

[*] Sectors 1 and 5 (Sector 1/5) was set as the reference for all comparisons.
[**] For sex estimation, males were the reference category against which females and ambiguous individuals were compared. Interaction terms are indicated by "✻".

Table 3.12: Results of the omnibus likelihood ratio test for the multinomial multiple logistic regression.

Omnibus Likelihood Ratio Test			
Predictor*	**χ^2**	**df**	**p****
Age-at-Death	8.57	4	0.073
$\delta^{13}C$	26.53	4	< .001
$\delta^{15}N$	47.13	4	< .001
Sex Estimation	43.75	8	< .001
NSL Size	11.13	4	0.025
Age-at-Death ✻ $\delta^{15}N$	13.61	4	0.009
Age-at-Death ✻ $\delta^{13}C$	12.73	4	0.013

[*] Results indicate whether a predictor (independent variable) was statistically significant in the overall model.
[**] Independent variables may be insignificant in the individual burial sector comparisons, but significant in the overall model. Significance threshold was set at $\alpha = 0.10$.

3.6.ii Statistical Significance

Monastic vs. Lay

The bivariate analyses on the monastic and lay cemeteries indicate that the monastic group has a significantly greater prevalence of NSLs, more NSLs per individual, and larger NSLs compared to lay individuals (Table 3.8). Bivariate analyses on the multivariable sample (n=196; Table 3.9) revealed only minor variations: $\delta^{15}N$ values were significantly lower for the monastic versus lay group ($p = 0.03$ vs $p = 0.06$ in the full sample), and NSL number was no longer significant in the multivariable sample. In contrast, $\delta^{13}C$, $\delta^{15}N$, estimated sex, NSL size, and interactions between $\delta^{15}N$ and NSL number and size were significant predictors in the binary multiple logistic regression on the multivariable sample (Table 3.10). These results indicate that the monastic group was likelier to have higher $\delta^{15}N$ values, higher $\delta^{13}C$ values, younger ages-at-death, and larger NSLs than the lay group.

The estimated marginal mean plots (EMM) visualize the logistic regression results (Figs. 3.5 and 3.6). For the binomial logistic regression, the larger confidence intervals for $\delta^{13}C$ values and NSL size at the upper ranges indicate a lack of precision (Fig. 3.5b and 3.5d). The rising confidence interval for $\delta^{13}C$ at values ≥ -18.0‰ may be from increased overlap between monastic and lay groups and fewer data points at this range. The large confidence interval for NSL size is likely due to the small number of individuals with NSLs spanning 4+ regions (n=2). The EMM for age-at-death (Fig. 3.5e) shows individuals are likelier to be from the lay cemetery at all ages. This seems to contradict the age-at-death distributions, as the monastic group has more individuals aged 45-60 yrs, and may indicate a non-linear relationship between age-at-death and the log-odds of being from monastic vs. lay cemetery.

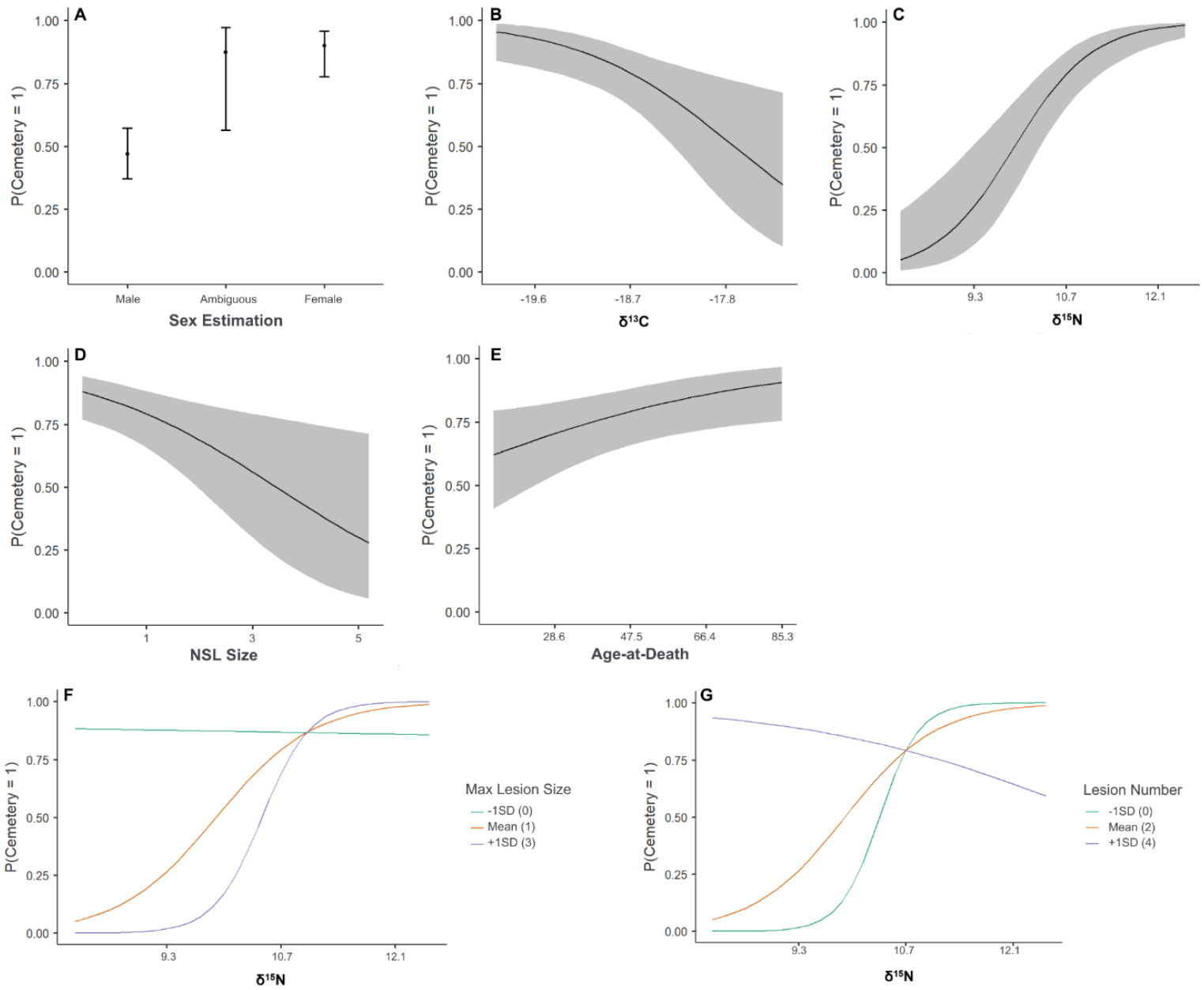

Figure 3.5: Estimated marginal mean (EMM) plots for the binary logistic regression results. The plots illustrate the relationship between the probability of belonging to the monastic (i.e., 0) or lay (i.e., 1) cemetery based on the value of the predictor variable, including: A) estimated sex, B) $\delta^{13}C$ values, C) $\delta^{15}N$ values, D) NSL size represented by the number of bone regions an NSL extended across, E) age-at-death, F) $\delta^{15}N$ values based on NSL size [interaction term], G) $\delta^{15}N$ values based on the number of NSLs an individual had [interaction term].

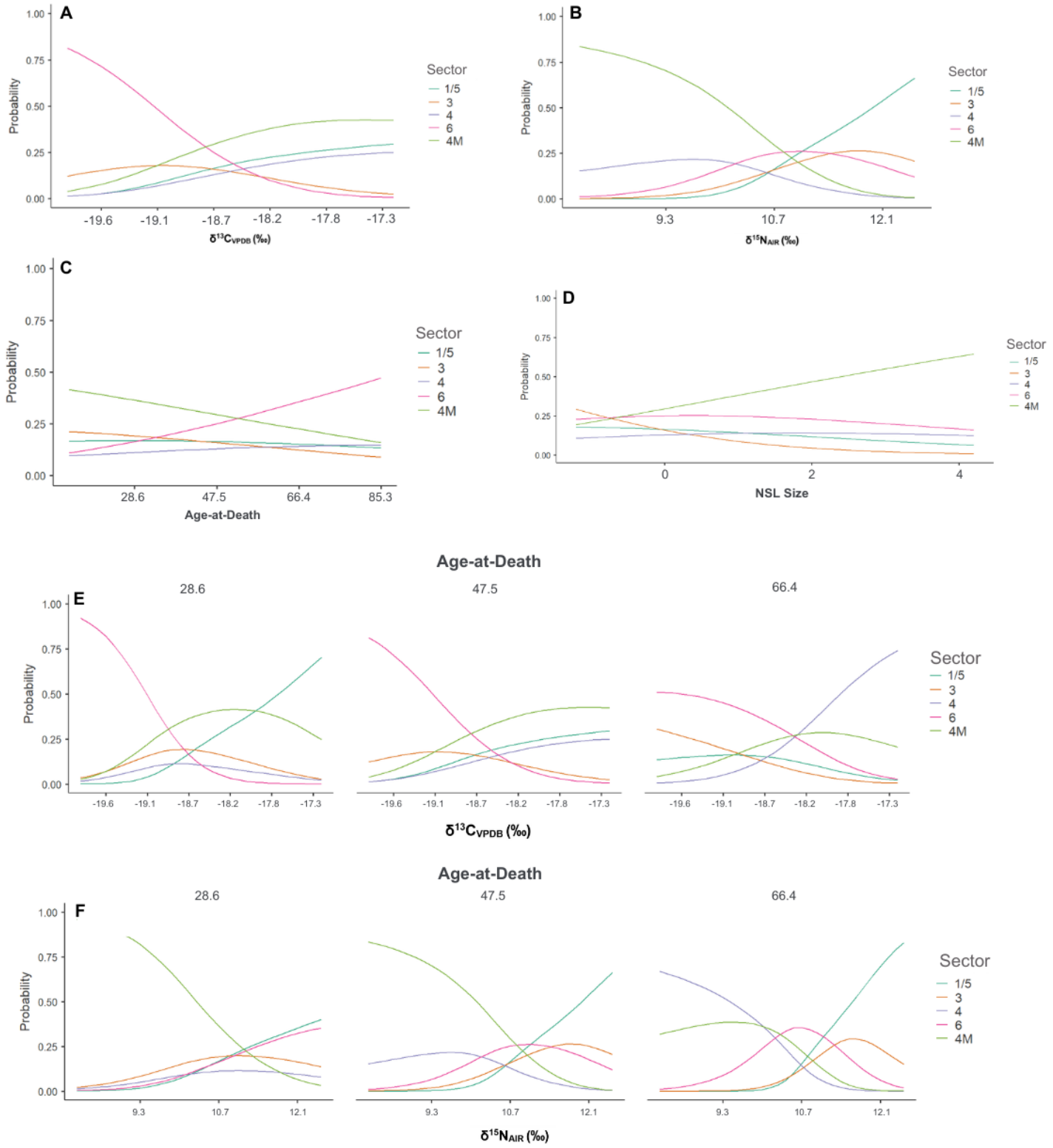

Figure 3.6: Estimated marginal mean plots (EMM) for the multinomial logistic regression. The EMMS visualizes the relationship between the probability of coming from a burial sector based on the independent variable value including: A) $\delta^{13}C$ values, B) $\delta^{15}N$ values, C) age-at-death, D) NSL size represented by the number of bone regions a NSL extends across, E) $\delta^{13}C$ values based on age-at-death [interaction term], F) $\delta^{15}N$ values based on age-at-death [interaction term].

Burial Sectors

The bivariate analyses examining differences between individual burial sectors indicate that $\delta^{13}C$, $\delta^{15}N$, age-at-death, NSL prevalence, and NSL number were statistically significant (Table 3.8). The only difference in results between the full and multivariable sample was that age-at-death was no longer significant ($p = 0.119$), and NSL size rather than NSL number was significant (Table 3.9). Lay individuals in Sectors 4 and 6 had significantly lower $\delta^{13}C$ values and Sector 4 had significantly lower $\delta^{15}N$ values than privileged individuals in Sectors 1 and 5 (Table 3.5). Sector 4 (lay) had a significantly greater mean age-at-death (56.6 yrs) than the other lay and monastic individuals (Table 3.4). Additionally, Sectors 3, 4, and 5 had significantly lower prevalences of NSLs in the full sample (Table 3.6). In the multivariable sample, this differed slightly, and only Sectors 3 and 5 had significantly lower prevalences of NSLs. Lastly, individuals from Sector 4M (monastic) and, to a lesser extent, Sector 4 (lay) had more NSLs per individual than the other burial sectors (Table 3.7).

The omnibus likelihood ratio test indicates that $\delta^{13}C$, $\delta^{15}N$, estimated sex, age-at-death, NSL size, and interactions between age-at-death and $\delta^{13}C$ and $\delta^{15}N$ were significant predictors of burial sector in the multinomial logistic regression (Table 3.12). These results suggest that Sector 6 and, to a lesser extent, Sector 4, were most likely to have individuals with lower $\delta^{13}C$ values ($\leq$ -18.1‰). The monastic group (4M) and individuals in Sector 4 were likeliest to have individuals with lower $\delta^{15}N$ values ($\leq$ 10.0‰), and privileged individuals from Sectors 1/5 the highest ($\geq$ 12.0‰). For age-at-death, Sector 6 was most likely to have individuals aged $\geq$ 66 years. Lastly, individuals in Sector 3 were the most likely to have no NSLs (NSL size "0"), and individuals from the monastic group were still likeliest to have larger NSLs extending across 2+ regions of their long bones.

3.6.iii Interaction Between Diet, Nonspecific Stress, and Age-at-Death

Significant interaction terms confirmed interactions between diet, nonspecific stress, and age-at-death in the multivariable analyses (Tables 3.10 and 3.12). The likelihood of an individual belonging to the monastic or lay cemetery based on $\delta^{15}N$ varies with NSL size and number (Fig. 3.5f and 3.5g). Monastic individuals with more and larger NSLs were likelier to have higher $\delta^{15}N$ values. In contrast, lay individuals with four NSLs were likelier to have lower $\delta^{15}N$ values than those with $\leq$ 2 NSLs. In the multinomial logistic regression, the probability of belonging to a specific burial sector based on $\delta^{13}C$ and $\delta^{15}N$ values changed with age-at-death (Fig. 3.6e and 3.6f). Individuals aged 47+ yrs in lay Sector 4 are likelier to have higher $\delta^{13}C$ values ($\geq$ -18.2‰), while privileged individuals aged 66+ in Sectors 1/5 are likelier to have lower $\delta^{13}C$ values. For $\delta^{15}N$, individuals aged 47+ yrs in lay Sectors 4 and 6 were likelier to have lower $\delta^{15}N$ values than their younger counterparts.

3.6.iv Measuring Differences

Effect sizes were calculated for the bivariate analyses when possible (Tables 3.8 and 3.9). The effect sizes were either small (i.e., Cramer's V and Cohen's D ≤ 0.2; Eta Squared ≤ .06) or moderate (i.e., Cramer's V and Cohen's D = 0.3-0.5; Eta Squared = 0.07-0.13), suggesting that group differences were often minimal, even when statistically significant. The binary logistic regression coefficients and EMM plots show that these variables had a greater impact on probability estimates when comparing monastic and lay groups, while the multinomial regression results aligned more closely. In the binary logistic regression, a one-unit increase in $\delta^{15}N$ (i.e., 0.7‰) resulted in individuals being 324% (OR 3.24, CI: 1.94-5.42) more likely to belong to the lay cemetery while an increase in $\delta^{15}N$ value dependent on NSL number resulted in individuals being 89% less likely to belong to the lay cemetery (OR: .21 CI: 0.10 – 0.47; Table 3.10).

3.7 DISCUSSION

The results confirmed differences between the bivariate and multiple logistic regression analyses regarding which variables were statistically significant, how values differed between groups, and the degree of differences. These differences culminate in a substantially different picture of intra-population variation in the Osor St. Peter's sample, where the multivariable results indicate a greater diversity of lived experiences within Osor's medieval population (see Table 3.13 for summary).

3.7.i Identifying Significant Variation

The bivariate results suggest that the primary difference between the monastic and lay groups was in the prevalence and character of nonspecific stress. The monastic individuals had significantly greater prevalence of NSLs, more NSLs per individual, and larger NSLs (Table 3.8). This, combined with a lack of significant difference in age-at-death between sectors, suggests that the monastic group may have experienced more chronic, long-term stressors that do not necessarily reflect resilience or survivorship compared to lay individuals.

Bivariate analyses show that lay individuals in Sector 4 had significantly higher ages-at-death, possibly reflecting health advantages or improved conditions during the 14^{th}–16^{th} centuries (Table 3.4). Paleopathological data indicate that mixed and privileged individuals in Sectors 3 and 5 had significantly lower NSL prevalence (Table 3.6). Given their lower mean ages-at-death (Table 3.4), this may suggest higher frailty, with individuals dying before NSLs could form—though survivorship or hazard modeling would be needed to confirm this. While $\delta^{13}C$ and $\delta^{15}N$ values varied significantly across sectors, the small mean differences (≤ 1.0‰) suggest meaningful dietary distinctions only between privileged individuals in Sectors 1 and 5 (highest $\delta^{13}C$ and $\delta^{15}N$ values) and lay people from basic and mixed burials in Sectors 4 and 6 (lowest values), respectively (Figure 3.3; Table 3.5).

The results of the multiple logistic regression analyses paint a substantially different picture and confirm interconnections between diet, nonspecific stress, and age-at-death in this sample (Table 3.13). The summary statistics and bivariate analyses (Tables 3.2, 3.4–3.9) suggest the differences are unlikely due to discrepancies between the full (n=341) and multivariable (n=196) samples. Binary logistic regression identified $\delta^{13}C$, $\delta^{15}N$, age-at-death, and NSL size as significant predictors (Table 3.10, Fig. 3.5), highlighting clearer distinctions between monastic and lay cemeteries. The monastic group likely consumed a diet lower in protein and/or richer in low-trophic marine resources (e.g., oysters, mussels), reflected in lower $\delta^{15}N$ and higher $\delta^{13}C$ values (Propst et al., in review). Additionally, lay individuals were more likely to reach the oldest ages-at-death (66+ years). Paired with the NSL results indicating the monastic group had larger NSLs, this may suggest greater exposure to chronic or long-term stressors contributing to earlier ages-at-death.

There was greater agreement between the bivariate and the multinomial logistic regression analyses. The multinomial logistic regression also confirmed that $\delta^{13}C$, $\delta^{15}N$, age-at-death, and NSL size significantly varied between the burial sectors. However, age-at-death was only statistically significant in the bivariate analyses with the full sample (n=341) and NSL size in the bivariate analysis with the multivariable sample (n=196). Regardless, both analyses indicate significant differences in diet, nonspecific stress, and age-at-death across St. Peter's burial sectors that may be linked to differences in socio-economic status. However, the way these factors varied between the burial sectors differed between the bivariate and multinomial logistic regression.

3.7.ii Understanding Variation

Controlling for the influence of other independent variables altered how groups appeared to differ, particularly for the multinomial logistic regression analysis of burial sectors. For diet, bivariate analyses suggested dietary differences were mainly between Sectors 1 and 5 (highest $\delta^{13}C$ and $\delta^{15}N$) and lay Sectors 4 and 6 (lowest values). However, the regression revealed more distinctions. For instance, while bivariate results showed minimal $\delta^{15}N$ differences between Sectors 3 and 4 (mean difference = 0.5‰; Table 3.5), the regression indicated that individuals with $\delta^{15}N$ around 10.0‰ were most likely from Sector 4, compared to 11.7‰ for Sector 3, when other factors were held constant (Fig 3.5b). This suggests Sector 4 individuals had less protein-rich diets than those in Sector 3, many of whom are likely associated with Osor's local aristocracy, further suggesting a link between higher protein intake and social status.

Multinomial logistic regression (Fig. 3.6c) shows that Sector 6, not Sector 4, had the highest likelihood of individuals aged 66 or older. When controlling for diet and nonspecific stress, this suggests greater longevity in Sector 6. The group also exhibited a distinct, likely terrestrial-protein-based diet. Together, these patterns highlight Sector 6 as a more distinct group within Osor's cemetery sample.

The multiple logistic regression revealed stronger and more meaningful group differences than bivariate analyses as well. While bivariate effect sizes were small to moderate (Tables 3.8 and 3.9), the multiple logistic regression results (Tables 3.10-3.12) indicated more significant trends. For example, although $\delta^{13}C$ and $\delta^{15}N$ differed by only 0.1‰ between monastic and lay cemeteries, higher $\delta^{15}N$ significantly increased the likelihood of burial in the lay cemetery.

Multinomial logistic regression (Figs. 3.5a and 3.5b) revealed more distinct differences in burial sector probabilities based on isotope values, highlighting stronger links between diet and social status in Osor. Privileged individuals in Sectors 1 and 5 had the highest $\delta^{13}C$ and $\delta^{15}N$ values, suggesting a protein- and marine-rich diet. Sector 3 showed slightly lower $\delta^{15}N$ values, likely reflecting its mixed-use nature with basic and privileged burials and possible some monastic burials. Sector 6 individuals—from both basic and privileged burials—had notably lower $\delta^{13}C$ values, indicating a more terrestrial diet and alternative status-diet associations. Sector 4 also had some of the lowest $\delta^{15}N$ values, consistent with its predominantly basic burials. These nuanced patterns would have been missed using only bivariate analyses and summary statistics.

3.7.iii Accounting for Interaction

Lastly, the multiple logistic regression analyses (Tables 3.10-3.12) identified significant interaction terms that would not have been evident in standard bivariate analyses (Tables 3.8 and 3.9). For the monastic group, interaction terms suggest a link between protein-rich diets (higher $\delta^{15}N$ values) and types of nonspecific stress, reflected in more and larger NSLs. Alternatively, higher $\delta^{15}N$ values may indicate stress-induced catabolic processes rather than dietary intake, though no links with $\delta^{13}C$ and age-at-death or NSL characteristics is evident (Fuller et al., 2005). In contrast, lay individuals with more NSLs tended to have lower $\delta^{15}N$ values. This suggests that diet alone did not drive NSL formation and that distinct biocultural processes affected each group. Similarly, interaction terms in the multinomial logistic regression (Table 3.12) indicated varying relationships between diet and age-at-death across burial sectors, possibly reflecting sector-specific patterns or internal heterogeneity. However, small sample sizes limit interpretation, and further targeted analysis is needed. Overall, these findings point to diverse lived experiences across Osor's monastic and secular communities (Table 3.13).

Table 3.13: Summary of results based on the bivariate and multivariable statistical analyses. See Chapter 4, Propst et al. (in review) for more in-depth analysis of the results.

Analysis	Variable	Bivariate		Multivariate	
		Results	Significance	Results	Significance
Variation between the monastic and lay communities	**Diet**	No statistically significant differences		The monastic group had higher $\delta^{13}C$ and lower $\delta^{15}N$ values	Monastic individuals likely relied on different forms of dietary proteins, and their diet may not have been as "protein-rich" as that of the lay population.
	Age-at-death	No statistically significant differences		Lay individuals were more likely to reach the oldest ages-at-death	The monastic lifestyle may have posed specific health risks, particularly in older age groups.
	Nonspecific Stress	The monastic group exhibited greater prevalences of NSLs, had more NSLs per individual, and larger NSLs	The monastic group may have experienced more chronic, long-term types of stress, resulting in more and larger NSLs.	Monastic individuals were more likely to have larger NSLs	The monastic group may have experienced more chronic, long-term types of stress, resulting in more and larger NSLs.

	Interaction	NA		Monastic individuals with more NSLs and larger NSLs were likelier to have higher $\delta^{15}N$ values.	Monastic individuals with more $\delta^{15}N$-rich diets may have faced greater chronic stressors, or higher $\delta^{15}N$ could reflect catabolic processes due to stress though no relationship with $\delta^{12}C$ is present.
				Lay individuals with more NSLs were more likely to have lower $\delta^{15}N$ values than those with ≤ 2 NSLs	Different biocultural processes mediated the relationship between diet and nonspecific stress for the lay population
Variation between the burial sectors (i.e., lay sectors 1, 3, 4, 5, and 6 and monastic sector 4M)	**Diet**	Privileged individuals in Sectors 1 and 5 had significantly higher $\delta^{13}C$ and $\delta^{15}N$ values than lay individuals in Sectors 4 and 6.	There is an association between status and diets, characterised by higher $\delta^{13}C$ and $\delta^{15}N$ values, likely reflecting more protein- and marine-rich diets.	Sector 6 individuals in basic and privileged burials were likeliest to have the lowest $\delta^{13}C$ values.	Individuals in Sector 6 had a diet that was more based on terrestrial protein overall, and the relationships between diet and status differ from those observed in Sectors 1, 3, and 5.

				Sector 4 was more likely to have the lowest $\delta^{15}N$ values of the lay cemetery	People with basic burials in Sector 4 had less protein-rich diets compared to those in other lay sectors, highlighting the connections between diet and status.
				Sector 3 individuals' $\delta^{13}C$ values are likely to be lower than Sectors 1, 5, and 4M, but their $\delta^{13}C$ values are like privileged individuals in Sectors 1 and 5	Sector 3 diets were protein-rich but more terrestrial than Sectors 1 and 5, highlighting connections between status and diet with mixed-status burials.
	Age-at-death	Sector 4 individuals had significantly greater ages-at-death	Sector 4 individuals may have experienced health advantages leading to higher ages-at-death	Sector 6 was most likely to have individuals aged ≥ 66 years.	Controlling diet and stress, Sector 6 individuals show greater ages-at-death, indicating unique trends and dietary patterns.
	Nonspecific Stress	Individuals in Sectors 3 and 5 had significantly lower prevalences of nonspecific stress	It suggests individuals show greater resilience or frailty based on age-at-death	The monastic group (Sector 4M) was most likely to have larger NSLs than all the lay burial sectors	The monastic group may have experienced more long-term chronic stressors compared to all other lay burial sectors

		Individuals in Sector 4 and 4M (monastic) have significantly more NSLs per individual.	This could indicate more long-term stressors and resiliency patterns due to Sector 4's higher mean ages-at-death.		
	Interaction	NA		The relationship between $\delta^{13}C$ and $\delta^{15}N$ values and age-at-death in Sectors 1/5, 4, and 6	Groups within Osor may have had different relationships between diet and age-at-death, indicating diverse socio-cultural practices, or there may be variability within the sample.

3.7.iv Challenges

The binomial logistic regression results (Fig. 3.5e) suggest a possible non-linear relationship between age-at-death and the log-odds for belonging to the monastic or lay cemetery. This could stem from the multi-modal (i.e., having multiple peaks) nature of age-at-death data and the lay cemetery having more individuals in the youngest and oldest age categories. Although the data suggest higher survivorship in the lay cemetery at older ages (66+), the non-linearity in log-odds can distort coefficient and odds ratio estimates, warranting cautious interpretation. This issue may also affect other logistic regression analyses involving similarly distributed age-at-death data.

Integrating the paleopathological data also posed challenges. The characteristics of NSLs can be valuable for better understanding the biological processes they reflect (Bisseret et al., 2015; Ragsdale, 1993; Ragsdale et al., 1981, 2018; Wenaden et al., 2005). However, these data are inherently correlated (e.g., number of NSLs is correlated with the number of bones affected, etc.). Additionally, NSL bone composition could not be incorporated into the logistic regression analyses due to complications with data coding and the small sample size of individuals with woven bone and mixed NSLs. While nonspecific lesions are common skeletal pathologies (Buikstra, 2019), integrating various measures of nonspecific stress requires careful consideration of which characteristics are most relevant and meaningful for the analysis. These

limits did constrain the multivariable paleopathological analysis in this study, and bivariate analyses were ultimately still used to supplement the multivariable analysis in Propst et al. (in review).

Additionally, sample size can be a particular issue when using multinomial logistic regression for dependent variables with ≥ 3 categories, as was the case for the burial sector in this study. In this instance, Sectors 1 and 5 had to be combined in the multinomial logistic regression to improve model fit. This resulted in the loss of some distinctions between the privileged individuals in Sectors 1 and 5 in the multivariable analyses regarding nonspecific stress and age-at-death. Sector 1 did not exhibit significantly lower prevalences of NSLs like Sector 5, and thus some granularity was lost in the multinomial logistic regression analysis.

Finally, the overall sample size was still a hurdle. Out of the 341 individuals in the full sample, only 57% of individuals (n=196/341) had adequate preservation to be included in the multivariable analysis. This can be considered fortuitous given the poor preservation of many bioarchaeological samples. It is also equally fortunate that the multivariable sample was representative of the full sample, which will not always be the case. Additionally, multinomial logistic regression requires larger sample sizes than binomial logistic regression analyses because the dependent variables have more categories (i.e., ≥ 3). Here, the multinomial logistic regression results suggest adequate precision (Table 3.11), but a larger sample size would still have been optimal. Lastly, missing data still needed to be imputed for all n=196 to be included in the sample following Wissler et al. (2022a, b).

3.8 CONCLUSION

This study is built upon a syndemic framework, which emphasizes the complex interconnections among highly interrelated categories of health data as central to understanding health-related conditions and lived experiences. St. Peter's Cemetery sample provided an interesting opportunity to explore the different interpretations possible when applying syndemics-oriented, integrative, and multivariable approaches versus discrete, bivariate approaches. The distribution and range of data between the separate groups within the sample (i.e., cemeteries and burial sectors) often resulted in groups having similar mean values despite varying trends in data distribution. The bivariate analyses, including t-tests and ANOVAs, proved limiting in this case since they are based upon mean differences, which can be insensitive to variation beyond central tendencies (i.e., means). This case study demonstrated that logistic regression analyses were better suited to identify trends in the data and illuminated intra-population variation more effectively.

Bivariate analyses are less complex, making them more robust when sample sizes are small or there is a lot of missing data. They are also advantageous for preliminary data screenings, research questions focusing on the relationships in narrower variable sets and are important for supplementing and/or complementing multivariable analyses when specific data types cannot be incorporated into multivariable analyses, as was the case with NSL data here.

However, when sample composition allows, multivariable analyses are advantageous when research incorporates data that are likely to be interconnected. Research from clinical, syndemic, historical, and bioarchaeological perspectives can help determine whether bioarchaeological data may be interconnected. These studies reveal instances of co-occurrence, identify likely interactions, and which contexts—such as war, colonization, and poverty—are likely to create environments where such interactions are likely to emerge (e.g., DeWitte et al., 2022; Larsen & Crespo, 2022; Singer, 2009; Singer et al., 2017).

Operationalizing syndemic frameworks through multivariable analyses a more nuanced understanding of intra-population variation in Osor, revealing diverse lived experiences between religious and lay communities, as well as within the lay population itself, shaped by socioeconomic class and other socio-cultural factors (Chapter 4, Propst et al., in review; Table 3.13). As Singer (2009) emphasizes, analyzing interrelated health data in isolation can distort interpretations. In this case, a bivariate approach would have significantly underestimated the complexity of Osor's skeletal sample and weakened connections to archaeological and historical evidence. This research demonstrated that multivariable analyses not only highlighted key areas of variation across Osor but also accounted for interactions between the independent variables, shaping a deeper understanding of how diet, nonspecific stress, and age-at-death varied within the osteological sample, strengthening interpretations, and opening new avenues for future research.

As integrative frameworks such as syndemic models of health and disease gain traction in bioarchaeological research, especially on epidemics (see DeWitte et al., 2022; Dimka et al., 2022; Larsen & Crespo, 2022; Schug & Halcrow, 2022), this case study shows how such integrative approaches seeking to address and examine interrelations in bioarchaeological data can be further operationalized across diverse contexts using multivariable analyses. Intra- and inter-population variation are central to bioarchaeological research and enable multi-scalar insights into population and regional dynamics over time and space. Dietary stable isotopes, nonspecific stress, and age-at-death are commonly used in this type of study (Katzenberg & Waters-Rist, 2018; Schrader, 2018; Weston, 2018), and can yield more meaningful interpretations when analyzed as interconnected rather than isolated variables.

The study highlighted important considerations and limitations in employing multivariable analyses like multiple logistic regression. The nature of age-at-death and nonspecific paleopathological data made their incorporation into the logistic regression analyses more challenging. Furthermore, sample size, representativeness, and missing data must always be considered. While multivariable analyses typically require larger sample sizes, the common guideline of 10 data points per variable allows their use in smaller samples when focusing on a limited number of variables. Advances in analytical methods also enable data collection from fragmented remains—for instance, a single tooth can now yield peptide-based sex estimates and stable isotope data on subadult diet and geographic origin. Well-preserved skeletons are not required, what matters is a good representation of the skeletal elements of interest. Additionally, Wissler et al. (2022a, 2022b) provide guidelines on how missing data can be dealt with, as in this study.

While not the only approach, the strategic use of multivariable and multivariate analyses offers a powerful means of addressing the complexities of bioarchaeological data. This case study reinforces key principles of syndemic models of health and disease and supports Singer's (2009) argument that analyzing interconnected health indicators in isolation can distort our interpretations. As syndemic frameworks gain momentum in bioarchaeology, this research demonstrates how multivariable methods can be effectively applied to explore these dynamics, emphasizing their value in generating deeper, more integrated understandings of past health and lived experience across a wide variety of research topics.

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SUPPLEMENTAL FILE 1: SUPPLEMENTAL DATA

3S.1 Expanded Methods

Age-at-death was estimated using Transition Analysis 2 (TA2), a multifactorial age-estimation method, scoring the features of the pubic symphysis and auricular surface. The maximum likelihood age estimates were used for statistical analysis (Boldsen et al., 2002). Timing of epiphyseal fusion by Cardoso (2008a, 2008b) was used to estimate the age of individuals with partial long bone fusion (Fig. 4.3). Sex was estimated using the traits outlined in (Buikstra & Ubelaker, 1994) for os coxae and crania (Acsádi & Nemeskéri, 1970; Milner, 1992; Phenice, 1969). Sex-based differences are not the focus of this analysis; however, Novak et al. (2021) and Šlaus (2000) found significant differences by sex in this region and time period. The data are therefore reported by sex to facilitate comparisons and control for these differences in the analysis.

S.1.i Analysis of Nonspecific Lesions

A macroscopic paleopathological analysis recorded osteoblastic (e.g., periosteal new bone formations) nonspecific lesions (NSLs) on long bones, recording their presence or absence, bone composition (lamellar, woven, or mixed), number per individual, number of affected bones, and maximum extent across bone regions (e.g., diaphysis and metaphysis, proximal to distal shaft). Areas of periosteal new bone growth surrounded by normal bone were recorded as a single lesion. Articular surfaces were not observed, and NSLs associated with fractures, entheseal changes, and osteoarthritis were excluded.

To account for preservation bias, each bone analyzed was scored for abrasion/erosion on a scale of 0 to 5+ following McKinley (2004), and an average abrasion/erosion score was calculated for each individual. Each bone and individual was scored for Anatomical Preservation Index (API) class on a scale of 1 (0% bone preserved) to 6 (100% bone preserved) following Bello et al. (2006) based on Dutour (1989). Long bones were considered “present” when at least 50% of the bone was preserved (i.e., API ≥ 4). Erosion/abrasion across the sample was slight to moderate (average grade = 1.6; patchy surface erosion). A chi-squared analysis found no significant association between abrasion/erosion grades and NSL presence (n=271; Spearman’s Rho = 0.009, p-value = 0.879), suggesting that taphonomic damage did not affect the paleopathological data.

S.1.ii Stable Isotope Analysis

Collagen extraction followed the Longin (1971) and Chisholm et al. (1982) protocols. The cleaned bone samples were demineralized in a series of 0.25M HCl (hydrochloric acid) washes, rinsed 3x in H_20, and washed in 0.1M NaOH (sodium hydroxide) to remove base-soluble contaminants. After further H_20 rinses, the samples were heated in a 0.001M HCl

solution at 80°C for 24 hours twice. The hot water-soluble collagen was then isolated and dried in a 60°C oven.

Prepared collagen samples were sent to the Ján Vizier lab in Ottawa for stable isotope analysis. Samples and standards were weighed into tin capsules and loaded into an elemental analyzer interfaced with a Delta Advantage isotope ratio mass spectrometer. All $\delta^{15}N$ data are reported in ‰ (per mil) vs. AIR. All $\delta^{13}C$ data are reported in ‰ VPDB. Repeated measures with internal standards (C-55 – L-glutamic acid) resulted in a standard error of 0.1‰ for both carbon and nitrogen. C:N ratios and %C and %N were examined to ensure adequate quality, specifically %C > 14.0% and %N > 4.8% (Ambrose, 1990). A slightly more conservative C:N ratio of 2.9 - 3.5 was used following Guiry & Szpak (2021). All samples meet quality control criteria (Table S3.5).

S.2 Stable Isotope Quality Control Indicators

Analytical precision is based on an internal standard (C- 55) (glutamic acid) and is better than ± 0.2‰ for both $\delta^{15}N$ and $\delta^{13}C$. Analytical precision is based on the internal check standard C- 55 $\delta^{15}N$ of -3.9 and $\delta^{13}C$ of − 28.5. Internal laboratory calibration standards are as follows: ($\delta^{15}N$, $\delta^{13}C$ in ‰): C-51 Nicotinamide ($\delta^{15}N$ 0.07‰, $\delta^{13}C$ − 22.95‰), C- 52 mix of ammonium sulphate + sucrose ($\delta^{15}N$ 16.58‰, $\delta^{13}C$ −11.94‰), C-54 caffeine ($\delta^{15}N$ −16.61‰, $\delta^{13}C$ −34.46‰). The check standards for each session (n=6) are reported in Table S3.1.

All $\delta^{15}N$ is reported as ‰ vs. AIR and normalized to internal standards calibrated to International standards IAEA-N1(+0.4‰), IAEA-N2(+20.3‰), USGS-40(-4.52‰) and USGS-41(47.57‰). The calibration standards are as good as or better than the check standard. In each case the calibration is R2 = 0.999x or better. All $\delta^{13}C$ is reported as ‰ vs. VPDB and normalized to internal standards calibrated to International standards IAEA-CH-6(-10.4‰), NBS-22(-29.91‰), USGS-40(-26.24‰) and USGS-41(37.76‰).

Supplementary Table S3.1: Checks and standards for each stable isotope session

Session ID	Check Standard	N	$\delta^{13}C$ (‰, VPDB) Mean and SD	$\delta^{15}N$ (‰, AIR) Mean and SD
1	C-55 (glutamic acid)	3	-28.4 ± 0.1	-4.0 ± 0.1
2	C-55 (glutamic acid)	4	-28.5 ± 0.1	-4.0 ± 0.1
3	C-55 (glutamic acid)	3	-28.6 ± 0.1	-3.9 ± 0.1
4	C-55 (glutamic acid)	3	-28.5 ± 0.1	-4.0 ± 0.1
5	C-55 (glutamic acid)	3	-28.5 ± 0.1	-3.9 ± 0.1
6	C-55 (glutamic acid)	3	-28.6 ± 0.1	-3.9 ± 0.1

S.3 Stable Isotope Methods for Samples From the Institute for Anthropological Research, Zagreb

Samples from rib bones were demineralized in 0.5 M aq. HCl at 4°C until demineralized. Samples were rinsed with de-ionized water and then gelatinized in acidic solution (pH 3) at 70°C for 48 hours. The liquid solution containing the gelatinized protein was frozen for 24 hours and then freeze-dried for 48 hours to obtain the final collagen product. Carbon and nitrogen isotope analysis was undertaken by Elemental Analysis - Isotope Ratio Mass Spectrometry (EA-IRMS).

Samples and references were weighed into tin capsules, sealed, and loaded into an auto-sampler on a Europa Scientific elemental analyser. and accelerated. The reference material used for $\delta^{13}C$ and $\delta^{15}N$ analysis of the collagen samples was IA-R068 (soy protein, $\delta^{13}C$V-PDB = -25.22 ‰, δ^{15}NAIR = 0.99 ‰). IA-R068, IA-R038 (L-alanine, $\delta^{13}C$V-PDB = -24.99 ‰, δ^{15}NAIR = -0.65 ‰), IA-R069 (tuna protein, $\delta^{13}C$V-PDB = -18.88 ‰, δ^{15}NAIR = 11.60 ‰) and a mixture of IAEA-C7 (oxalic acid, $\delta^{13}C$V-PDB = -14.48 ‰) and IA-R046 (ammonium sulphate, δ^{15}NAIR = 22.04 ‰) were run as quality control check samples during analysis of the collagen samples. IA-R068, IA-R038 and IA-R069 are calibrated against and traceable to IAEA-CH-6 (sucrose, $\delta^{13}C$V-PDB = -10.449 ‰) and IAEA-N-1 (ammonium sulphate, δ^{15}NAIR = 0.40 ‰). IA-R046 is calibrated against and traceable to IAEA-N-1. IAEA-C7, IAEA-CH-6 and IAEA-N-1 are inter-laboratory comparison standards distributed by the International Atomic Energy Agency, Vienna.

S.4 Comparison Between Current Study and Institute for Anthropological Research Stable Isotope values

Stable isotope analysis had previously been completed for n=40 rib samples from the Osor St. Peter osteological sample. Of these previously run samples, n=12 was re-run following the procedures outlined by Propst et al. (in review) (Chapter 4) to ensure that differing methods and lab protocols did not produce significantly different results. A paired t-test was used to test for significantly different $\delta^{15}N$ and $\delta^{13}C$ results between the two labs. The results indicate that $\delta^{13}C$ values were not statistically significantly different. The $\delta^{15}N$ values were significantly different, but the mean difference was 0.2‰ and thus within the realm of standard error. This indicates that the stable isotope results did not meaningfully differ from one another.

Supplementary Table S3.2: $\delta^{13}C$ and $\delta^{15}N$ values descriptive statistics for Propst et al. (2025) and the Institute's stable isotope samples

	N	Mean	Median	SD	SE
$\delta^{13}C$ (Propst)	12	-18.6	-18.5	0.355	0.1025
$\delta^{13}C$ (Inst)	12	-18.5	-18.5	0.326	0.0942
$\delta^{15}N$ (Propst)	12	11.0	11.2	0.705	0.2035
$\delta^{15}N$ (Inst)	12	10.9	11.0	0.626	0.1807

Supplementary Table S3.3: Results of t-test comparing the stable isotopes run for Propst et al. (in review) and those previously collected at the Institute for Anthropological Research

			Statistic	df	p	Mean difference
$\delta^{13}C$ (Propst)	$\delta^{13}C$ (Inst)	Student's t	-0.407	11.0	0.692	-0.0241
$\delta^{15}N$ (Propst)	$\delta^{15}N$ (Inst)	Student's t	3.365	11.0	0.006	0.1767

Supplementary Table S3.4: Missing Completely at Random (MCAR) results

EM Means[a]

AgeatDeathSimplified	SI_Carbon_Rib	SexEstimationMFAU	SI_Nitrogen_Rib
47.4787	-18.7215	.37	10.6909

a. Little's MCAR test: Chi-Square = 10.378, DF = 10, Sig. = .408

S.5 Stable Isotope Data

Osor St. Peter Human Values

Supplementary Table S3.5: Stable Isotope results for Osor St. Peter's Human Samples. QCD indicates Quality Control Datum.

Sample ID	Weight (mg)	$\delta^{13}C$ (‰) vpdb	%wt C	$\delta^{15}N$ (‰) air	%wt N	Atomic C:N	Yield %
2	0.7	-18.52	51.0	10.82	18.1	3.29	9.0
2 QCD	0.7	-18.61	48.2	10.92	17.1	3.29	9.0
5	0.7	-18.20	48.8	11.56	17.2	3.31	6.0
7	0.7	-18.51	39.0	11.04	13.9	3.27	7.0
8	0.7	-18.43	47.4	11.65	16.7	3.31	4.0
9	0.7	-19.55	41.5	10.07	14.8	3.26	5.0
11	0.7	-19.03	27.6	10.9	9.8	3.28	4.0
12	0.7	-18.26	44.1	11.73	15.6	3.30	9.0
12 QCD	0.7	-18.24	42.7	11.76	15.1	3.30	9.0
17	0.7	-18.36	36.3	10.97	12.9	3.27	5.0
18	0.7	-18.39	50.7	11.22	18.3	3.23	5.0
20	0.7	-19.74	30.1	9.87	10.5	3.36	4.0
24	0.7	-19.15	34.8	11.06	12.4	3.27	6.0
33	0.7	-19.17	34.5	10.91	12.5	3.23	4.0
34	0.7	-18.71	44.8	10.74	15.9	3.29	4.0
36	0.7	-18.61	40.6	11.47	14.4	3.29	5.0
41	0.7	-18.52	39.7	10.56	14.2	3.25	4.0
50	0.7	-18.42	45.3	11.20	16.1	3.28	4.0
53	0.7	-18.55	51.7	10.73	18.4	3.28	8.0
53 QCD	0.7	-18.56	44.2	10.67	15.7	3.28	8.0
59	0.7	-18.69	44.1	10.73	15.8	3.25	5.0
61	0.7	-19.08	52.6	10.43	18.9	3.25	4.0

63	0.7	-18.57	49.6	11.34	17.4	3.32	4.0
64	0.7	-18.44	49.0	11.56	17.3	3.30	4.0
65	0.7	-18.32	37.7	11.39	13.6	3.24	4.0
66	0.7	-19.13	41.6	10.27	14.9	3.25	4.0
67	0.7	-18.84	42.9	10.29	15.2	3.29	7.0
69	0.7	-18.54	44.7	10.80	15.9	3.28	8.0
69 QCD	0.7	-18.49	42.2	10.66	15.1	3.26	8.0
70	0.7	-18.61	53.6	11.18	18.8	3.32	4.0
71	0.7	-18.99	49.1	10.59	17.3	3.31	4.0
77	0.7	-18.60	42.6	11.39	15.1	3.29	4.0
78	0.7	-18.76	46.8	11.67	16.6	3.29	7.0
79	0.7	-18.30	43.8	12.21	15.5	3.30	4.0
81	0.7	-18.85	36.0	10.26	13.0	3.22	6.0
84	0.7	-18.74	50.3	11.33	17.6	3.33	5.0
85	0.7	-19.42	36.3	9.95	13.1	3.24	5.0
90	0.7	-18.03	49.4	11.61	17.4	3.31	4.0
94	0.7	-18.62	44.6	10.85	15.8	3.29	3.0
95	0.7	-18.59	43.0	10.56	15.3	3.28	4.0
97	0.7	-19.23	46.1	10.06	16.3	3.30	5.0
98	0.7	-18.33	54.4	11.47	19.6	3.24	4.0
101	0.7	-18.93	46.1	11.09	16.4	3.28	6.0
101 QCD	0.7	-19.03	39.5	10.84	14.0	3.28	6.0
102	0.7	-19.21	40.3	11.17	14.4	3.27	5.0
105	0.7	-19.10	52.0	10.23	18.4	3.30	4.0
111	0.7	-18.17	46.9	10.33	16.5	3.31	8.0
111 QCD	0.7	-18.22	47.7	10.49	16.7	3.33	8.0
112	0.7	-18.75	49.7	10.80	17.7	3.27	4.0
114	0.7	-18.07	51.7	11.82	18.4	3.28	6.0

120	0.7	-18.15	52.5	11.16	18.8	3.26	13.0
120 QCD	0.7	-18.11	49.9	11.19	17.9	3.25	13.0
128	0.7	-17.33	38.5	11.76	13.8	3.25	5.0
129	0.7	-18.62	43.8	11.01	15.6	3.27	10.0
129 QCD	0.7	-18.64	47.3	11.05	16.7	3.30	10.0
130	0.7	-17.86	47.9	11.44	17.2	3.25	10.0
130 QCD	0.7	-17.84	40.2	11.17	14.4	3.25	10.0
131	0.7	-18.97	40.8	9.58	14.5	3.28	3.0
143	0.7	-19.46	40.6	9.05	14.6	3.25	4.0
144	0.7	-18.76	41.5	10.53	14.9	3.26	4.0
147	0.7	-18.73	55.7	10.19	19.9	3.26	6.0
149	0.7	-19.16	40.6	10.19	14.5	3.28	5.0
153	0.7	-18.63	54.3	10.28	18.9	3.35	4.0
156	0.7	-19.03	48.4	10.19	17.1	3.30	6.0
157	0.7	-19.51	25.7	11.08	9.1	3.29	7.0
164	0.7	-19.21	35.0	10.07	12.6	3.23	6.0
165	0.7	-19.22	39.9	10.27	14.4	3.24	5.0
171	0.7	-19.05	43.2	9.95	15.5	3.25	4.0
177	0.7	-19.03	49.0	10.33	17.5	3.27	6.0
179	0.7	-18.64	48.6	10.40	16.9	3.35	4.0
182	0.7	-18.64	43.9	11.34	15.4	3.32	5.0
186	0.7	-19.21	50.1	9.99	17.6	3.32	5.0
187	0.7	-18.42	49.2	10.35	17.1	3.36	5.0
188	0.7	-19.33	42.3	9.60	15.1	3.27	4.0
190	0.7	-18.65	46.6	10.23	16.1	3.38	4.0
194	0.7	-18.67	44.8	11.22	15.8	3.31	4.0
195	0.7	-18.57	28.6	10.47	10.2	3.26	4.0
196	0.7	-18.75	43.9	10.06	15.8	3.24	6.0

197	0.7	-18.40	52.9	11.90	18.8	3.28	3.0
199	0.7	-19.62	45.5	10.10	16.3	3.26	6.0
199 QCD	0.7	-19.63	44.6	10.28	15.9	3.27	6.0
202	0.7	-18.91	46.8	10.95	16.6	3.29	5.0
203	0.7	-18.77	40.5	11.46	14.3	3.31	1.0
205	0.7	-18.57	44.3	10.81	15.8	3.27	4.0
206	0.7	-19.38	38.7	9.51	13.7	3.30	4.0
208	0.7	-19.10	49.5	10.56	17.6	3.28	4.0
212	0.7	-17.75	45.7	8.32	16.4	3.25	5.0
213	0.7	-19.49	51.4	10.58	18.4	3.26	4.0
216	0.7	-19.08	44.2	10.24	15.5	3.33	4.0
218	0.7	-18.86	45.8	10.19	16.1	3.32	6.0
219	0.7	-18.11	55.5	11.15	19.2	3.37	4.0
222	0.7	-19.05	37.2	10.43	13.1	3.30	5.0
223	0.7	-18.57	51.7	10.67	18.4	3.28	6.0
223 QCD	0.7	-18.51	45.0	10.53	16.1	3.26	6.0
224	0.7	-18.95	51.1	10.41	18.3	3.26	4.0
225	0.7	-18.57	42.0	10.34	14.9	3.29	5.0
226	0.7	-18.41	50.6	10.88	17.7	3.33	9.0
226 QCD	0.7	-18.44	43.1	10.74	15.3	3.28	9.0
227	0.7	-19.23	44.6	10.63	16.1	3.23	5.0
228	0.7	-17.96	44.4	11.61	15.8	3.28	6.0
229	0.7	-17.55	51.4	11.92	18.4	3.26	7.0
229 QCD	0.7	-17.49	38.2	11.80	13.6	3.27	7.0
231	0.7	-18.72	31.6	9.99	11.4	3.23	5.0
232	0.7	-19.16	40.9	9.96	14.6	3.26	4.0
233	0.7	-18.56	44.4	10.57	15.9	3.26	5.0
235	0.7	-19.14	50.1	11.72	17.4	3.36	9.0

238	0.7	-19.29	47.3	10.22	16.8	3.28	4.0
241	0.7	-19.34	42.7	9.49	15.1	3.30	4.0
243	0.7	-18.57	36.7	10.82	13.1	3.27	6.0
245	0.7	-19.18	38.3	10.51	13.6	3.28	5.0
246	0.7	-18.90	47.5	10.11	17.0	3.26	8.0
248	0.7	-19.06	46.0	10.47	16.3	3.29	6.0
251	0.7	-18.51	43.3	11.73	15.5	3.26	4.0
252	0.7	-18.99	52.6	10.01	18.9	3.25	2.0
253	0.7	-18.71	50.7	10.78	17.6	3.36	6.0
257	0.7	-19.02	48.2	10.63	17.2	3.27	7.0
258	0.7	-18.54	49.3	11.26	17.6	3.27	4.0
259	0.7	-18.76	35.2	10.27	12.7	3.24	5.0
260	0.7	-18.85	44.2	10.04	15.7	3.28	4.0
261	0.7	-19.02	42.3	10.18	14.9	3.32	5.0
264	0.7	-18.97	28.5	10.62	10.1	3.28	3.0
265	0.7	-17.97	42.1	10.64	14.9	3.30	9.0
265 QCD	0.7	-17.92	45.4	10.58	16.0	3.31	9.0
266	0.7	-18.33	48.0	11.75	16.8	3.33	7.0
268	0.7	-18.67	43.2	11.28	15.4	3.27	3.0
269	0.7	-18.91	36.9	10.21	13.2	3.26	4.0
270	0.7	-18.33	50.2	10.60	18.0	3.25	4.0
271	0.7	-18.82	39.6	10.50	13.9	3.32	4.0
272	0.7	-19.25	41.4	10.47	14.8	3.26	6.0
272 QCD	0.7	-19.30	31.6	10.39	11.3	3.27	6.0
280	0.7	-17.96	43.3	11.16	15.4	3.28	4.0
281	0.7	-18.25	36.2	11.04	13.0	3.25	6.0
281 QCD	0.7	-18.24	34.5	11.29	11.3	3.27	6.0
282	0.7	-18.90	40.9	10.28	14.5	3.28	6.0

283	0.7	-18.28	44.4	10.64	15.8	3.28	9.0
284	0.7	-19.08	41.1	9.96	14.6	3.29	7.0
285	0.7	-19.07	45.6	10.57	16.2	3.28	4.0
286	0.7	-18.47	54.6	10.91	19.5	3.27	6.0
287	0.7	-19.13	43.7	9.45	15.4	3.31	4.0
289	0.7	-18.83	48.4	10.60	17.3	3.26	6.0
290	0.7	-18.33	52.2	10.24	18.6	3.27	9.0
293	0.7	-18.56	46.8	10.38	16.5	3.31	5.0
294	0.7	-19.31	58.6	9.78	20.9	3.27	5.0
297	0.7	-18.29	56.9	11.38	20.5	3.24	5.0
298	0.7	-18.58	50.4	11.81	17.7	3.32	4.0
299	0.7	-18.11	57.8	10.73	20.7	3.26	8.0
305	0.7	-18.25	44.9	10.99	15.8	3.31	5.0
306	0.7	-18.19	45.2	10.60	15.9	3.32	4.0
307	0.7	-18.28	40.6	10.76	14.6	3.25	7.0
308	0.7	-18.01	49.1	11.29	17.3	3.31	5.0
309	0.7	-18.45	51.4	10.55	18.0	3.33	5.0
310	0.7	-18.83	51.2	10.48	17.7	3.37	5.0
314	0.7	-19.26	20.2	9.91	7.2	3.29	5.0
315	0.7	-19.01	60.9	10.84	21.7	3.27	6.0
316	0.7	-18.78	27.4	10.50	9.8	3.27	7.0
317	0.7	-18.70	44.5	10.05	16.0	3.24	4.0
318	0.7	-19.49	44.5	10.99	15.7	3.31	4.0
319	0.7	-18.79	50.5	10.61	17.7	3.33	4.0
321	0.7	-18.33	53.1	11.28	18.5	3.35	5.0
322	0.7	-18.67	47.2	10.77	16.5	3.34	4.0
323	0.7	-18.02	51.1	11.09	17.9	3.33	6.0
324	0.7	-18.49	46.4	10.41	16.7	3.24	5.0

327	0.7	-18.62	31.7	9.33	11.3	3.27	6.0
328	0.7	-18.85	62.3	9.73	22.2	3.27	5.0
328 QCD	0.7	-18.82	48.7	9.57	17.5	3.25	5.0
330	0.7	-18.63	41.8	9.88	14.9	3.26	4.0
334	0.7	-18.21	35.7	10.98	12.8	3.26	6.0
336	0.7	-18.61	44.2	10.75	15.7	3.28	8.0
336 QCD	0.7	-18.55	47.7	10.91	16.8	3.30	8.0
338	0.7	-18.67	37.3	9.80	13.3	3.27	4.0
340	0.7	-18.35	43.0	10.72	15.2	3.30	6.0
341	0.7	-17.95	45.2	10.70	16.1	3.27	9.0
344	0.7	-18.57	42.3	10.75	15.0	3.29	5.0
345	0.7	-18.30	49.6	10.97	17.3	3.34	4.0
346	0.7	-19.53	45.0	10.58	15.9	3.30	3.0
347	0.7	-19.88	44.4	10.02	16.0	3.24	4.0
349	0.7	-18.54	41.2	10.53	14.5	3.31	5.0
350	0.7	-18.79	42.2	10.62	15.1	3.26	5.0
353	0.7	-19.07	41.7	10.13	14.7	3.32	4.0
354	0.7	-19.12	42.1	10.02	15.1	3.25	4.0
355	0.7	-19.39	38.8	9.71	13.9	3.26	4.0
356	0.7	-18.66	52.5	10.62	18.9	3.24	5.0
358	0.7	-18.05	45.8	11.38	16.1	3.32	3.0
359	0.7	-19.08	44.6	11.42	16.0	3.25	3.0
360	0.7	-18.89	30.8	10.74	11.0	3.25	4.0
361	0.7	-18.78	46.1	10.45	16.6	3.24	5.0
362	0.7	-18.97	33.9	10.94	12.2	3.25	4.0
364	0.7	-19.07	46.2	10.44	16.4	3.29	5.0
365	0.7	-18.50	44.9	10.11	16.0	3.27	5.0
366	0.7	-18.61	55.0	10.41	19.8	3.24	5.0

367	0.7	-18.19	54.1	10.79	19.1	3.30	5.0
368	0.7	-18.29	52.9	11.24	18.9	3.26	4.0
369	0.7	-18.93	48.8	9.77	17.5	3.25	5.0
370	0.7	-19.02	41.3	9.81	14.7	3.28	4.0
374	0.7	-19.34	40.1	9.58	14.5	3.23	5.0
379	0.7	-18.85	49.2	9.81	17.5	3.28	4.0
380	0.7	-19.22	53.8	9.91	19.3	3.25	5.0
381	0.7	-18.34	16.0	9.67	5.6	3.31	4.0
384	0.7	-18.63	44.1	10.89	15.6	3.30	14.0
384 QCD	0.7	-18.63	47.0	11.08	16.6	3.30	14.0
385	0.7	-18.52	46.4	10.18	16.8	3.22	4.0
386	0.7	-18.28	50.4	12.1	17.7	3.32	8.0
388	0.7	-18.56	30.1	10.15	10.9	3.23	4.0
393	0.7	-19.46	29.6	10.58	10.6	3.25	4.0
396	0.7	-18.46	52.7	10.24	18.9	3.25	6.0
397	0.7	-19.45	56.0	9.72	19.5	3.35	14.0
397 QCD	0.7	-19.44	47.9	9.77	16.9	3.31	14.0
398	0.7	-19.05	46.5	10.83	16.4	3.31	5.0
399	0.7	-19.27	43.2	10.38	15.4	3.27	4.0
410	0.7	-17.97	55.0	12.38	19.3	3.32	6.0
411	0.7	-18.69	50.6	10.94	18.2	3.24	4.0
412	0.7	-18.57	45.6	11.35	16.3	3.26	5.0
414	0.7	-18.56	50.9	11.37	17.8	3.33	11.0
414 QCD	0.7	-18.56	35.2	11.32	12.5	3.30	11.0
415	0.7	-18.30	30.7	10.10	11.0	3.25	7.0
416	0.7	-17.67	51.5	12.11	18.6	3.23	6.0
417	0.7	-18.58	39.5	11.28	14.0	3.28	8.0
417 QCD	0.7	-18.58	49.8	11.39	17.7	3.28	8.0

418	0.7	-18.31	40.0	12.24	14.2	3.29	10.0
419	0.7	-18.13	42.9	11.63	15.3	3.27	6.0
421	0.7	-18.20	43.9	11.13	15.4	3.32	8.0
422	0.7	-18.35	42.0	10.77	14.9	3.30	3.0
429	0.7	-19.10	29.1	10.55	10.5	3.23	6.0
432	0.7	-18.81	45.8	10.41	16.3	3.28	4.0
434	0.7	-18.74	47.3	10.70	17.0	3.24	3.0
436	0.7	-18.99	44.2	10.15	15.8	3.26	4.0
439	0.7	-18.37	41.3	10.54	14.7	3.27	4.0
442	0.7	-19.29	32.2	11.00	11.5	3.27	5.0
443	0.7	-18.22	45.7	10.73	16.3	3.27	4.0
444	0.7	-19.03	52.1	10.49	18.3	3.32	4.0
445	0.7	-18.87	55.6	11.78	19.9	3.26	7.0
446	0.7	-18.45	42.5	11.96	15.2	3.26	4.0
448	0.7	-18.12	50.7	11.15	17.8	3.32	4.0
450	0.7	-19.32	43.0	11.04	14.3	3.51	5.0
451	0.7	-19.49	16.3	11.12	5.7	3.33	5.0
454	0.7	-18.27	34.0	11.40	12.2	3.25	3.0
455	0.7	-18.42	50.2	11.57	18.1	3.23	4.0
456	0.7	-18.11	48.1	11.38	17.3	3.24	5.0
457	0.7	-19.74	57.0	10.00	20.6	3.23	3.0
459	0.7	-19.01	51.9	10.27	18.3	3.31	4.0
460	0.7	-19.20	59.9	10.45	21.3	3.28	6.0
460QCD	0.7	-19.26	40.0	10.43	14.3	3.27	6.0
463	0.7	-18.69	37.7	10.50	13.6	3.24	5.0
464	0.7	-19.37	30.5	9.57	10.9	3.25	3.0
466	0.7	-19.61	47.2	11.12	16.8	3.28	3.0
467	0.7	-18.31	48.6	10.99	17.4	3.26	4.0

468	0.7	-18.50	48.1	11.84	17.1	3.28	4.0
469	0.7	-19.49	40.8	11.67	14.5	3.29	5.0
475	0.7	-19.61	34.7	10.09	12.2	3.33	4.0
477	0.7	-18.94	41.2	9.76	14.9	3.24	4.0
478	0.7	-18.95	42.4	11.25	15.4	3.21	3.0
480	0.7	-19.58	39.6	8.95	14.3	3.24	7.0
481	0.7	-18.97	47.1	10.70	16.5	3.33	5.0
484	0.7	-19.01	35.4	11.42	12.6	3.29	5.0
488	0.7	-19.19	41.6	9.97	14.9	3.25	6.0
489	0.7	-19.00	54.5	9.93	19.5	3.26	6.0
490	0.7	-19.60	39.2	10.44	14.0	3.27	7.0
491	0.7	-19.15	29.5	10.20	10.4	3.31	3.0
500	0.7	-18.17	47.6	11.81	16.8	3.30	3.0
511	0.7	-18.64	40.4	11.31	14.3	3.29	5.0
513	0.7	-18.70	46.0	10.41	16.6	3.23	4.0
517	0.7	-18.87	48.8	11.46	17.5	3.25	3.0
519	0.7	-18.42	46.8	12.14	16.9	3.23	5.0
525	0.7	-18.57	47.6	11.11	17.0	3.27	5.0
531	0.7	-18.20	46.6	10.70	16.4	3.31	5.0
535	0.7	-18.76	42.2	10.63	15.1	3.26	5.0
541	0.7	-19.49	43.6	9.42	15.6	3.26	4.0
54A	0.7	-18.57	40.5	11.35	14.5	3.26	8.0
62A	0.7	-19.05	44.7	10.25	16.1	3.24	5.0
62B	0.7	-18.85		10.22			5.0
NA (58)	0.7	-18.77	54.7	8.45	17.9	3.36	13.0

SUPPLEMENTAL FILE 2: DATA SHEET

Table S3.6: Full dataset

Individual	Multivariable Sample	Sector	Age-at-Death	Sex Estimation	API Score	d13C	d15N	Abrasion	Long Bones Absent/Present	NSL Absent/Present	NSL Lesion #	Bones Affected #	Max NSL Length (Region)	NSL Composition
2	N	1	*	M	3	-18.5	10.8	3	1	1	1	1	1	Mixed
5	Y	1	64.0	M	4	-18.2	11.6	2.5	1	0	0	0	*	*
7	N	3	25.8	F	2	-18.5	11.0	0	0	*	*	*	*	*
8	N	6	24.4	F	2	-18.4	11.7	2	1	0	0	0	*	*
9	Y	6	42.0	F	5	-19.6	10.1	2	1	0	0	0	*	*
11	Y	6	29.0	M	5	-19.0	10.9	2.5	1	1	3	3	2	Lamellar
12	Y	6	43.7	M	4	-18.3	11.7	3	1	0	0	0	*	*
13	N	6	*	M	2	*	*	0	0	*	*	*	*	*
15	N	3	15.0	M	2	*	*	0	0	*	*	*	*	*
16	N	3	*	M	2	*	*	0	0	*	*	*	*	*
17	N	3	82.1	M	3	-18.4	11.0	2	1	0	0	0	*	*
18	Y	3	*	M	4	-18.4	11.2	2.5	1	0	0	0	*	*
20	Y	3	53.2	F	5	-19.7	9.9	2	1	1	1	1	1	Lamellar
21	N	3	14.0	*	2	*	*	*	1	0	0	0	*	*
24	Y	3	40.4	M	5	-19.2	11.1	2	1	0	0	0	*	*
26	N	3	82.6	A	2	*	*	0	0	*	*	*	*	*
33	Y	3	72.5	M	5	-19.2	10.9	2	1	1	7	5	1	Lamellar
34	Y	3	18.4	M	5	-18.7	10.7	2	1	0	0	0	*	*
35	N	3	21.5	M	2	*	*	*	1	0	0	0	*	*
36	Y	3	50.5	M	5	-18.6	11.5	1.5	1	0	0	0	*	*
41	N	3	48.5	M	3	-18.5	10.6	*	1	1	1	1	2	Lamellar
43	N	3	31.9	M	2	*	*	*	1	1	2	2	4	Lamellar
45	N	3	*	M	*	-18.7	10.8	*	*	*	*	*	*	*
47	N	3	26.1	F	2	*	*	*	1	0	0	0	*	*

50	Y	3	31.6	M	4	-18.4	11.2	1	1	1	1	1	1	Lamellar
53	Y	3	24.8	M	5	-18.6	10.7	1	1	1	7	3	1	Mixed
59	Y	3	72.3	M	4	-18.7	10.7	1	1	1	2	2	1	Lamellar
60	N	3	*	M	2	*	*	0	0	*	*	*	*	*
61	Y	3	68.5	F	4	-19.1	10.4	3	1	0	0	0	*	*
63	Y	3	77.1	M	3	-18.6	11.3	1	1	1	2	2	1	Lamellar
64	Y	3	49.6	M	5	-18.4	11.6	1	1	1	3	3	3	Lamellar
65	Y	3	33.3	M	4	-18.3	11.4	2	1	0	0	0	*	*
66	Y	3	26.3	F	4	-19.1	10.3	1	1	1	2	2	1	Mixed
67	Y	3	15.5	A	4	-18.8	10.3	1	1	0	0	0	*	*
68	N	3	*	M	*	-18.5	12.1	*	*	*	*	*	*	*
69	N	3	*	M	3	-18.5	10.8	1	1	1	1	1	2	Mixed
70	Y	3	26.2	M	5	-18.6	11.2	2	1	0	0	0	*	*
71	N	3	38.8	M	2	-19.0	10.6	1	1	0	0	0	*	*
72	N	3	*	M	2	*	*	*	1	0	0	0	*	*
73	N	3	*	M	2	*	*	*	1	0	0	0	*	*
77	N	3	52.9	M	4	-18.6	11.4	1	1	0	0	0	*	*
78	Y	3	24.9	M	5	-18.8	11.7	2	1	1	1	1	1	Lamellar
79	Y	3	31.0	M	5	-18.3	12.2	1	1	1	1	1	1	Lamellar
81	Y	3	29.0	F	5	-18.9	10.3	2	1	1	3	3	1	Mixed
82	N	3	49.2	M	2	*	*	0	0	*	*	*	*	*
84	N	3	68.4	M	2	-18.7	11.3	1	1	1	2	1	1	Mixed
85	Y	3	27.7	A	4	-19.4	10.0	1	1	0	0	0	*	*
90	Y	3	70.1	M	4	-18.0	11.6	2	1	0	0	0	*	*
91	N	3	*	F		-18.8	9.8	*	*	*	*	*	*	*
94	Y	3	29.0	M	5	-18.6	10.9	1	1	0	0	0	*	*
95	Y	3	63.7	M	5	-18.6	10.6	1	1	1	2	1	1	Lamellar
97	N	3	23.1	M	3	-19.2	10.1	1	1	0	0	0	*	*
98	Y	3	72.5	M	5	-18.3	11.5	1	1	0	0	0	*	*
101	Y	3	21.1	M	5	-18.9	11.1	3	1	0	0	0	*	*

102	N	3	*	A	3	-19.2	11.2	1	1	0	0	0	*	*
105	Y	3	69.9	F	4	-19.1	10.2	*	1	1	1	1	1	Lamellar
107	N	4	*	*	2	*	*	*	1	0	0	0	*	*
109	N	4	*	F	2	*	*	*	1	0	0	0	*	*
111	N	4	*	F	3	-18.2	10.3	1	1	0	0	0	*	*
112	Y	4	44.7	F	4	-18.8	10.8	3	1	0	0	0	*	*
114	Y	4	23.1	M	4	-18.1	11.8	2.5	1	1	6	3	3	Mixed
116	N	4	*	*	2	*	*	*	1	0	0	0	*	*
119	N	4M	*	F	2	*	*	0	0	*	*	*	*	*
120	Y	4	44.3	M	5	-18.2	11.2	1	1	1	6	5	2	Lamellar
121	N	4M	26.7	M	2	*	*	0	0	*	*	*	*	*
125	N	4M	*	M	2	*	*	0	0	*	*	*	*	*
126	N	4M	*	F	2	*	*	0	0	*	*	*	*	*
128	Y	4M	70.6	M	5	-17.3	11.8	2.5	1	1	2	2	1	Lamellar
129	Y	4M	57.7	M	4	-18.6	11.0	3	1	1	3	2	2	Mixed
130	Y	4M	47.5	A	5	-17.9	11.4	2	1	1	12	5	2	Mixed
131	N	4	36.0	M	3	-19.0	9.6	*	1	0	0	0	*	*
135	N	4	*	M	2	*	*	1	1	0	0	0	*	*
138	N	4	19.5	*	2	*	*	0	0	*	*	*	*	*
143	N	4	74.1	F	3	-19.5	9.1	1	1	0	0	0	*	*
144	Y	4	18.5	F	3	-18.8	10.5	1	1	0	0	0	*	*
147	Y	4	*	F	4	-18.7	10.2	*	1	0	0	0	*	*
149	Y	4	16.5	*	4	-19.2	10.2	1	1	0	0	0	*	*
150	N	4	*	*	2	*	*	1	1	0	0	0	*	*
153	N	4	73.5	A	2	-18.6	10.3	1	1	0	0	0	*	*
156	Y	4	72.2	F	5	-19.0	10.2	2	1	1	1	1	1	Lamellar
157	N	4	*	*	*	-19.5	11.1	*	*	*	*	*	*	*
164	Y	4	79.4	M	5	-19.2	10.1	1	1	0	0	0	*	*
165	N	4	73.4	M	2	-19.2	10.3	1	1	1	1	1	2	Lamellar
167	N	4	41.8	F	2	*	*	1	0	*	*	*	*	*

171	N	4	*	*	*	-19.1	10.0	*	*	*	*	*	*	*
177	Y	4	*	*	3	-19.0	10.3	1	1	0	0	0	*	*
179	N	4	78.4	M	3	-18.6	10.4	1	1	1	1	1	1	Lamellar
180	N	4	39.5	M	2	*	*	3	1	0	0	0	*	*
182	N	4	82.1	M	2	-18.6	11.3	2.5	1	0	0	0	*	*
184	N	4	59.6	*	2	*	*	0	0	*	*	*	*	*
185	N	4	73.1	F	2	*	*	1	1	0	0	0	*	*
186	Y	4	38.8	F	4	-19.2	10.0	1	1	1	1	1	1	Lamellar
187	Y	4	75.7	M	5	-18.4	10.4	1	1	1	1	1	1	Lamellar
188	N	4	75.7	M	3	-19.3	9.6	1	1	0	0	0	*	*
190	Y	4	76.2	M	3	-18.7	10.2	1	1	1	7	4	2	Lamellar
194	N	4	36.5	M	3	-18.7	11.2	1	1	0	0	0	*	*
195	N	4	29.0	M	3	-18.6	10.5	*	1	0	0	0	*	*
196	Y	4	68.6	M	4	-18.8	10.1	1	1	0	0	0	*	*
197	Y	4	29.0	F	5	-18.4	11.9	1	1	0	0	0	*	*
199	N	4	36.7	A	2	-19.6	10.1	1	1	0	0	0	*	*
202	Y	4	39.6	M	3	-18.9	11.0	1	1	1	3	3	2	Lamellar
203	N	4M	*	*	2	-18.8	11.5	0	0	*	*	*	*	*
205	Y	4	52.4	M	3	-18.6	10.8	1	1	0	0	0	*	*
206	N	4	74.0	F	2	-19.4	9.5	1	1	0	0	0	*	*
208	Y	4	45.5	M	5	-19.1	10.6	1	1	1	10	6	2	Mixed
209	N	4	70.1	M	2	*	*	1.5	1	1	1	1	1	Lamellar
212	Y	4	62.8	M	5	-17.8	8.3	1	1	1	4	4	1	Mixed
213	N	4	73.5	M	3	-19.5	10.6	1	1	0	0	0	*	*
214	N	4	30.5	M	3	*	*	1	1	0	0	0	*	*
216	Y	4	70.2	M	3	-19.1	10.2	1	1	1	3	2	2	Lamellar
218	N	4	67.5	*	3	-18.9	10.2	1	1	1	2	2	1	Lamellar
219	N	4M	23.2	M	3	-18.1	11.2	2	1	0	0	0	*	*
220	N	4M	80.6	M	2	*	*	0	0	*	*	*	*	*
221	N	4M	76.2	M	2	*	*	0	0	*	*	*	*	*

Y	4M	70.6	M	3	-19.1	10.4	1	1	0	0	0	*	*
Y	4M	30.1	M	4	-18.6	10.7	2	1	1	3	2	1	Mixed
Y	4M	59.4	M	5	-19.0	10.4	1	1	1	2	2	2	Lamellar
Y	4M	69.8	M	4	-18.6	10.3	1	1	1	3	1	2	Lamellar
Y	4M	75.1	M	4	-18.4	10.9	1	1	1	6	4	2	Lamellar
Y	4M	45.6	M	5	-19.2	10.6	1	1	1	2	2	3	Mixed
Y	4M	56.3	M	4	-18.0	11.6	2	1	1	9	3	3	Mixed
Y	4M	41.2	M	4	-17.6	11.9	2.5	1	1	4	2	1	Lamellar
N	4M	66.5	M	2	*	*	0	0	*	*	*	*	*
Y	4M	59.5	M	3	-18.7	10.0	2	1	0	0	0	*	*
Y	4M	62.4	M	4	-19.2	10.0	1	1	1	3	3	1	Lamellar
Y	4M	68.9	M	5	-18.6	10.6	1	1	1	2	2	1	Lamellar
Y	4M	46.0	M	4	-19.1	11.7	1	1	1	1	1	1	Lamellar
N	4M	78.2	M	4	-19.3	10.2	1	1	0	0	0	*	*
Y	4M	66.2	M	4	-19.3	9.5	3.5	1	1	1	1	1	Lamellar
Y	4M	24.3	M	4	-18.6	10.8	1.5	1	1	4	4	5	Mixed
Y	4	52.2	M	5	-19.2	10.5	2	1	1	3	2	1	Lamellar
Y	4M	52.2	M	5	-18.9	10.1	1	1	1	6	4	2	Lamellar
Y	4M	36.2	F	5	-19.1	10.5	2	1	1	1	1	1	Lamellar
Y	5	66.0	M	5	-18.5	11.7	3	1	1	3	3	2	Mixed
Y	4	80.0	M	4	-19.0	10.0	2	1	1	6	5	1	Lamellar
N	4	72.7	M	3	-18.7	10.8	1	1	0	0	0	*	*
N	4M	26.3	M	2	*	*	0	0	*	*	*	*	*
Y	4M	32.3	M	4	-19.0	10.6	2	1	1	1	1	1	Mixed
Y	4M	62.9	M	4	-18.5	11.3	1.5	1	1	2	2	1	Lamellar
Y	4M	*	*	3	-18.8	10.3	1	1	1	5	3	3	Mixed
Y	4	76.0	M	3	-18.9	10.0	1	1	1	3	3	1	Mixed
Y	4	69.2	M	3	-19.0	10.2	2.5	1	1	4	4	1	Mixed
Y	4M	24.3	M	3	-19.0	10.6	1	1	1	2	2	1	Lamellar
N	4M	50.0	M	4	-18.0	10.6	2	1	1	2	2	1	Woven

266	Y	4M	41.6	M	3	-18.3	11.8	2	1	0	0	0	*	*
267	N	4M	67.5	M	3	*	*	1	1	0	0	0	*	*
268	Y	4M	34.0	M	5	-18.7	11.3	1	1	1	1	1	1	Lamellar
269	N	4	41.6	M	3	-18.9	10.2	*	1	0	0	0	*	*
270	Y	4	72.0	M	3	-18.3	10.6	1	1	1	1	1	1	Lamellar
271	Y	4	30.2	M	4	-18.8	10.5	1	1	1	2	1	1	Lamellar
272	Y	4M	*	*	4	-19.3	10.5	1	1	1	1	1	1	Lamellar
276	N	4M	18.2	M	2	*	*	0	0	*	*	*	*	*
277	N	4M	30.5	M	3	*	*	1	1	0	0	0	*	*
278	N	4M	25.3	M	2	*	*	0	0	*	*	*	*	*
280	Y	4M	22.5	A	5	-18.0	11.2	1.5	1	1	1	1	2	Mixed
281	Y	4M	29.6	M	5	-18.3	11.0	1	1	0	0	0	*	*
282	N	4M	35.1	M	3	-18.9	10.3	1.5	1	1	1	1	1	Lamellar
283	Y	4M	33.7	M	5	-18.3	10.6	1	1	0	0	0	*	*
284	N	4	69.5	M	2	-19.1	10.0	1	1	0	0	0	*	*
285	N	4	80.1	M	2	-19.1	10.6	1	1	0	0	0	*	*
286	Y	4M	76.8	M	5	-18.5	10.9	1.5	1	1	7	6	3	Lamellar
287	Y	4	55.9	M	4	-19.1	9.5	1	1	1	5	4	1	Woven
288	N	4	71.1	M	2	*	*	*	1	0	0	0	*	*
289	Y	4M	27.6	M	5	-18.8	10.6	2	1	0	0	0	*	*
290	Y	4M	46.3	M	4	-18.3	10.2	1	1	1	9	4	3	Lamellar
293	Y	4M	41.3	M	5	-18.6	10.4	1	1	1	7	5	1	Mixed
294	N	4M	17.5	A	4	-19.3	9.8	2	1	0	0	0	*	*
297	Y	4M	41.8	M	5	-18.3	11.4	1	1	1	1	1	1	Mixed
298	N	8	66.8	M	5	-18.6	11.8	2.5	1	1	2	2	1	Lamellar
299	Y	4M	46.1	M	5	-18.1	10.7	1	1	0	0	0	*	*
300	N	4M	*	M	2	*	*	0	0	*	*	*	*	*
301	N	4M	*	M	2	*	*	0	0	*	*	*	*	*
302	N	4M	71.7	M	2	*	*	1	1	1	1	1	1	Lamellar
303	N	4M	*	M	2	*	*	0	0	*	*	*	*	*

Y	4M	79.0	M	5	-18.3	11.0	1.5	1	1	7	6	2	Mixed
N	4M	60.5	M	3	-18.2	10.6	1	1	0	0	0	*	*
Y	4M	56.5	M	4	-18.3	10.8	1	1	1	3	2	2	Mixed
Y	4M	74.5	M	4	-18.0	11.3	1.5	1	1	7	3	2	Mixed
Y	4M	36.9	F	5	-18.5	10.6	1	1	1	1	1	2	Lamellar
Y	4M	32.2	M	5	-18.8	10.5	1	1	1	1	1	1	Lamellar
N	4M	78.9	M	2	*	*	1	1	1	3	2	3	Woven
N	4M	22.8	M	2	*	*	0	0	*	*	*	*	*
Y	4M	60.3	M	4	-19.3	9.9	1	1	1	2	1	1	Lamellar
Y	4M	35.4	M	4	-19.0	10.8	2	1	1	2	1	2	Mixed
Y	4M	23.5	M	3	-18.8	10.5	2	1	1	3	3	3	Lamellar
Y	4M	64.6	M	5	-18.7	10.1	1.5	1	1	2	2	1	Lamellar
N	4M	24.6	M	4	-19.5	11.0	1	1	0	0	0	*	*
Y	4M	38.3	M	5	-18.8	10.6	1	1	1	7	3	2	Lamellar
Y	4M	36.6	M	4	-18.3	11.3	1.5	1	1	11	8	3	Woven
Y	4M	35.3	M	4	-18.7	10.8	1	1	1	1	1	1	Lamellar
Y	1	25.0	F	4	-18.0	11.1	3	1	1	5	4	3	Mixed
Y	4M	38.9	M	5	-18.5	10.4	1	1	0	0	0	*	*
N	4M	50.5	M	2	*	*	1	1	1	2	1	1	Mixed
Y	4M	67.9	M	5	-18.6	9.3	1	1	0	0	0	*	*
Y	4M	69.2	M	5	-18.9	9.7	1	1	1	1	1	1	Woven
N	4M	*	M	2	*	*	0	0	*	*	*	*	*
Y	4M	42.7	M	5	-18.6	9.9	1	1	1	1	1	1	Lamellar
N	4M	60.0	M	2	*	*	0	0	*	*	*	*	*
N	4M	37.0	M	2	*	*	0	0	*	*	*	*	*
Y	1	83.4	F	5	-18.2	11.0	2	1	1	3	3	3	Mixed
N	4M	59.7	M	2	*	*	1	1	1	2	1	2	Mixed
Y	1	77.6	F	5	-18.6	10.8	*	1	1	3	3	1	Mixed
Y	4M	76.4	M	4	-18.7	9.8	1	1	0	0	0	*	*
N	4M	39.9	M	2	*	*	0	0	*	*	*	*	*

Y	4M	41.1	M	4	-18.4	10.7	1	1	1	8	3	3	Mixed
Y	1	24.0	M	5	-18.0	10.7	2.5	1	1	6	5	1	Lamellar
Y	4M	60.3	M	4	-18.6	10.8	1	1	0	0	0	*	*
N	4M	62.4	M	3	-18.3	11.0	1	1	0	0	0	*	*
Y	4M	45.0	M	5	-19.5	10.6	1	1	1	4	3	3	Lamellar
Y	4M	58.4	M	3	-19.9	10.0	1	1	1	1	1	2	Lamellar
N	4M	30.6	M	2	*	*	0	0	*	*	*	*	*
N	4M	72.4	M	3	-18.5	10.5	1	1	1	4	3	2	Lamellar
N	4M	30.8	M	3	-18.8	10.6	1	1	1	5	3	1	Mixed
N	4M	43.9	M	3	*	*	1	1	0	0	0	*	*
N	4M	34.0	M	2	*	*	0	0	*	*	*	*	*
Y	4M	62.6	M	5	-19.1	10.1	1	1	0	0	0	*	*
Y	4M	42.6	M	4	-19.1	10.0	1	1	1	6	4	2	Mixed
N	4M	*	A	3	-19.4	9.7	2	1	0	0	0	*	*
Y	4M	35.6	M	4	-18.7	10.6	1	1	1	5	3	1	Mixed
Y	4M	30.6	M	4	-18.1	11.4	1	1	1	3	3	2	Lamellar
Y	4M	18.1	M	5	-19.1	11.4	1	1	0	0	0	*	*
Y	4M	33.8	M	5	-18.9	10.7	1	1	0	0	0	*	*
Y	4M	23.5	M	5	-18.8	10.5	2.5	1	1	4	2	2	Lamellar
Y	4M	36.8	M	5	-19.0	10.9	1	1	1	4	2	1	Lamellar
N	4M	26.7	F	3	*	*	1	1	0	0	0	*	*
Y	4M	71.0	M	5	-19.1	10.4	1	1	1	6	5	1	Lamellar
N	4M	66.5	F	3	-18.5	10.1	1	1	1	4	4	5	Mixed
Y	4M	53.8	M	5	-18.6	10.4	1	1	1	1	1	2	Lamellar
Y	4M	36.6	M	5	-18.2	10.8	2.5	1	0	0	0	*	*
Y	4M	28.9	M	5	-18.3	11.2	2	1	1	2	2	1	Lamellar
Y	4M	54.6	M	5	-18.9	9.8	2.5	1	1	1	1	1	Lamellar
Y	4M	46.9	F	5	-19.0	9.8	1	1	0	0	0	*	*
N	4M	52.0	F	2	*	*	0	0	*	*	*	*	*
Y	4M	49.4	F	4	-19.3	9.6	1	1	0	0	0	*	*

375	N	5	21.4	M	2	*	*	2	1	1	1	1	1	Lamellar
376	N	5	38.4	M	2	*	*	0	0	*	*	*	*	*
378	N	5	35.3	F	2	-19.1	10.7	0	0	*	*	*	*	*
379	Y	4M	65.7	M	4	-18.9	9.8	1.5	1	1	5	5	4	Lamellar
380	Y	4M	65.7	F	5	-19.2	9.9	1	1	1	2	2	1	Lamellar
381	Y	4M	43.8	F	4	-18.3	9.7	1	1	1	1	1	1	Lamellar
383	N	5	52.8	M	4	-18.3	11.2	2	1	0	0	0	*	*
384	N	1	69.2	M	4	-18.6	10.9	2	1	1	2	2	1	Mixed
385	N	4M	64.2	F	3	-18.5	10.2	2	1	0	0	0	*	*
386	Y	1	43.4	M	4	-18.3	12.1	3	1	0	0	0	*	*
387	N	4M	57.9	A	2	*	*	0	0	*	*	*	*	*
388	Y	4M	31.8	F	3	-18.6	10.2	2	1	0	0	0	*	*
389	Y	5	65.5	F	4	-19.0	10.7	1	1	0	0	0	*	*
390	Y	5	29.9	M	4	-18.3	11.8	1	1	1	4	4	3	Lamellar
391	Y	5	70.4	M	3	-18.5	11.7	3	1	1	2	2	1	Lamellar
392	N	4M	27.3	F	3	*	*	2	1	0	0	0	*	*
393	Y	4M	30.8	F	5	-19.5	10.6	1.5	1	0	0	0	*	*
395	N	4M	26.2	F	3	*	*	2	1	0	0	0	*	*
396	Y	4M	29.4	F	4	-18.5	10.2	2.5	1	0	0	0	*	*
397	Y	4M	65.9	A	5	-19.5	9.7	2.5	1	1	2	2	1	Lamellar
398	Y	6	*	M	4	-19.1	10.8	1	1	1	1	1	1	Lamellar
399	Y	6	21.1	F	5	-19.3	10.4	1	1	0	0	0	*	*
401	N	6	21.5	M	3	*	*	2	1	1	4	3	1	Mixed
410	Y	1	28.9	F	4	-18.0	12.4	1.5	1	0	0	0	*	*
411	N	1	14.0	*	3	-18.7	10.9	2	1	1	1	1	1	Lamellar
412	Y	1	26.0	F	5	-18.6	11.4	3	1	1	1	1	1	Lamellar
414	Y	6	61.0	M	4	-18.6	11.4	2	1	1	2	2	2	Lamellar
415	Y	1	27.4	F	3	-18.3	10.1	3	1	1	1	1	1	Lamellar
416	Y	1	19.7	M	3	-17.7	12.1	3.5	1	1	2	2	3	Lamellar
417	Y	1	24.0	F	5	-18.6	11.3	3	1	1	2	2	1	Lamellar

Y	1	31.8	M	4	-18.3	12.2	3	1	1	1	1	1	Lamellar
Y	1	25.9	F	4	-18.1	11.6	2.5	1	0	0	0	*	*
N	6	62.1	M	3	*	*	1	1	1	1	1	1	Lamellar
Y	6	76.7	M	4	-18.2	11.1	1	1	1	1	1	1	Lamellar
Y	6	75.9	M	4	-18.4	10.8	1	1	1	2	2	1	Mixed
Y	6	66.2	A	4	-19.1	10.6	1	1	1	2	2	1	Lamellar
N	6		A		-19.4	9.5	*	*	*	*	*	*	*
N	5	61.3	F	3	-18.8	10.4	2	1	1	1	1	2	Lamellar
Y	5	19.5	A	4	-18.7	10.7	2.5	1	0	0	0	*	*
Y	5	38.3	F	5	-19.0	10.2	1	1	1	1	1	1	Lamellar
N	6	44.7	M	2	*	*	1	1	0	0	0	*	*
N	5	*	*	2	*	*	1	1	1	2	2	3	Lamellar
N	5	43.1	F	3	-18.4	10.5	1	1	0	0	0	*	*
N	5		A		-18.3	12.0	*	*	*	*	*	*	*
N	6	32.6	M	3	-19.3	11.0	1	1	0	0	0	*	*
N	5	*	*	2	-18.2	10.7	0	0	*	*	*	*	*
Y	6	19.9	F	5	-19.0	10.5	1	1	0	0	0	*	*
Y	6	28.6	M	4	-18.9	11.8	2	1	0	0	0	*	*
Y	5	19.5	M	5	-18.5	12.0	1	1	0	0	0	*	*
N	6	22.0	M	2	-18.1	11.2	1	1	0	0	0	*	*
Y	5	77.9	M	5	*	*	1.5	1	0	0	0	*	*
Y	6	44.3	M	5	-19.5	11.1	1.5	1	1	1	1	1	Lamellar
Y	5	27.0	M	5	-18.3	11.4	2	1	1	1	1	1	Lamellar
N	5	27.5	F	4	-18.4	11.6	1	1	0	0	0	*	*
Y	5	25.9	F	5	-18.1	11.4	1.5	1	0	0	0	*	*
Y	6	24.0	F	5	-19.7	10.0	2	1	0	0	0	*	*
N	6	69.5	M	2	-19.0	10.3	1	1	1	1	1	1	Lamellar
Y	6	55.5	F	5	-19.2	10.5	2.5	1	0	0	0	*	*
Y	6	69.5	M	4	-18.7	10.5	1	1	1	2	2	1	Mixed
Y	6	37.1	A	4	-19.4	9.6	1	1	0	0	0	*	*

465	N	6	27.6	A	2	*	*	1	1	0	0	0	*	*
466	N	6	*	*	2	-19.6	11.1	0	0	*	*	*	*	*
467	Y	6	40.2	M	3	-18.3	11.0	2	1	1	4	3	2	Mixed
468	Y	6	*	A	4	-18.5	11.8	2	1	1	2	2	1	Lamellar
469	N	6	15.4	A	2	-19.5	11.7	2	1	0	0	0	*	*
471	N	6	64.3	F	2	*	*	*	1	0	0	0	*	*
475	Y	6	67.9	M	5	-19.6	10.1	2	1	1	3	2	1	Lamellar
477	Y	6	60.9	A	5	-18.9	9.8	2	1	1	1	1	1	Lamellar
478	Y	6	32.9	M	4	-19.0	11.3	1	1	1	1	1	1	Lamellar
480	Y	6	65.9	F	5	-19.6	9.0	2	1	1	1	1	1	Mixed
481	Y	6	71.3	A	5	-19.0	10.7	2	1	1	3	3	2	Mixed
483	N	6	74.0	M	2	*	*	*	1	0	0	0	*	*
484	Y	6	75.2	M	4	-19.0	11.4	*	1	1	2	2	1	Mixed
486	N	6	19.7	F	3	*	*	1	1	0	0	0	*	*
487	Y	6	26.5	M	4	-19.4	10.1	1	1	1	1	1	1	Lamellar
488	Y	6	59.8	M	5	-19.2	10.0	1	1	1	6	5	1	Lamellar
489	Y	6	77.2	F	5	-19.0	9.9	1	1	0	0	0	*	*
490	Y	6	74.4	M	4	-19.6	10.4	2	1	1	1	1	1	Lamellar
491	N	6	*	M	2	-19.2	10.2	*	1	0	0	0	*	*
500	Y	5	*	*	3	-18.2	11.8	2.5	1	0	0	0	*	*
511	N	5	*	F	2	-18.6	11.3	2.5	1	0	0	0	*	*
513	Y	6	64.6	M	4	-18.7	10.4	2	1	1	2	1	2	Lamellar
514	N	5	27.1	F	3	*	*	1	1	1	4	4	4	Mixed
517	Y	5	25.3	F	5	-18.9	11.5	1	1	0	0	0	*	*
519	Y	5	40.3	M	4	-18.4	12.1	3	1	0	0	0	*	*
520	N	5	*	*	2	*	*	2.5	1	1	1	1	1	Lamellar
522	N	5	21.5	M	2	*	*	2.5	1	0	0	0	*	*
525	Y	5	46.8	M	5	-18.6	11.1	3.5	1	0	0	0	*	*
526	N	5	28.2	F	4	-19.0	10.3	1	1	1	1	1	1	Lamellar
531	Y	5	60.4	F	4	-18.2	10.7	2	1	0	0	0	*	*

535	Y	6	75.9	F	5	-18.8	10.6	2	1	1	1	1	1	Lamellar
536	N	6	*	M	2	*	*	*	1	0	0	0	*	*
538	Y	6	69.7	F	4	-19.1	9.7	2	1	1	1	1	1	Mixed
539	Y	6	38.7	F	4	-19.3	10.0	3	1	1	1	1	1	Lamellar
540	N	6	36.7	M	3	-19.0	10.5	1.5	1	0	0	0	*	*
541	Y	6	30.3	F	4	-19.5	9.4	1	1	0	0	0	*	*
543	N	6	*	*	3	*	*	1	1	0	0	0	*	*
545	Y	5	34.6	F	4	-18.3	9.7	1	1	1	2	2	1	Lamellar
548	Y	6	24.3	M	5	-19.0	10.2	1	1	0	0	0	*	*
549	Y	6	38.3	F	4	-18.9	10.3	1	1	1	3	3	1	Lamellar
54A	Y	3	77.0	M	2	-18.6	11.4	2.5	1	0	0	0	*	*
54B	N	3	15.0	M	2	*	*	2	1	1	2	2	2	Lamellar
62A	N	3	16.5	A	2	-19.1	10.3	1	1	0	0	0	*	*
62B	Y	3	14.0	A	4	-18.9	10.2	2	1	0	0	0	*	*
Burial 5.101	N	5	18.0	M	2	*	*	0	0	*	*	*	*	*
NA (58)	N	3	*	M	2	-18.8	8.5	0	0	*	*	*	*	*
NA (US 3.1016)	N	3	*	F	2	*	*	*	1	0	0	0	*	*

Dataset Legend

Individual	Individual Identifier Number
Multivariable Sample	Whether or not an individual is part of the smaller (n=196) multivariable sample
Sector	Burial sector an individual was buried in. Sector 4M references the monastic burials (i.e., Sector 4 Monastic) and Sector 4 are lay burials.
Age-at-Death	The age-at-death estimates calculated using Transition Analysis 2 and Cardoso et al (2008a, 2008b)
Sex Estimation	Estimated sex using standards from Buikstra and Ubelaker (1994).
API Score (Class 1-6)	API score for the entire skeleton following Bello et al. (2006) after Dutour (1989). Some individuals overall presentation was < 50%, but they had ≥50% of their long bones present and were therefore included in the multivariable sample
d13C	Rib bone collagen delta 13 Carbon values
d15N	Rib bone collagen delta 15 Nitrogen values
Abrasion (McKinley 2004)	Abrasion/erosion score following McKinley (2004)
Long Bones Absent/Present	Long bones were considered "present" when ≥ 50% were present
NSL Absent/Present	Whether nonspecific lesions were absent or present
Nonspecific Lesion #	The number of nonspecific lesions an individual had
Bones Affected #	The number of bones that had nonspecific lesions per individual
Max NSL Length (Region)	The maximum number of bone regions (i.e., proximal/distal diaphysis and metaphysis, and proximal, middle, and distal shaft) that a nonspecific lesion extended across. N=7 regions.
NSL Composition	The type of bone nonspecific osteoblastic lesions was comprised of (i.e., lamellar, mixed, or woven)

Anatomical Preservation Index (Bello et al. 2006)	
API Score	**Description**
Class 1	Bone not preserved (0% of bone preserved);
Class 2	1–24% of bone preserved

Class 3	25–49% of bone preserved
Class 4	50–74% of bone preserved
Class 5	75–99% of bone preserved
Class 6	Bone completely preserved (100% of bone preserved)

NSL Presence/Absence Score	**Description**
0	Absent
1	Present

Sex Estimation Score	**Description**
M	Male
F	Female
A	Ambiguous
U	Unknown (No scorable elements)

Erosion/Abrasion (McKinley 2004)	
Score	**Description**
0	Surface morphology clearly visible with fresh appearance to bone and no modifications
1	Slight and patchy surface erosion
2	More extensive surface erosion than grade 1 with deeper surface penetration
3	Most of the bone surface affected by some degree of erosion (by root action); general morphology maintained but detail of parts of surface masked by erosive action
4	All of the bone surface affected by erosive action; general profile maintained and depth of modification not uniform across whole surface
5	Heavy erosion across whole surface, completely masking normal surface morphology, with some modification of profile
5+	As grade 5 but with extensive penetrating erosion resulting in modification of profile

CHAPTER 4: INTRAPOPULATION VARIATION IN ST. PETER'S MEDIEVAL (10^{TH}-16^{TH} CENTURIES) CEMETERY (OSOR, CROATIA): A MULTIVARIABLE ANALYSIS OF DIET, NONSPECIFIC STRESS, AND MORTALITY

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ABSTRACT

This study investigates intrapopulation variation within the medieval cemetery from Osor, Croatia (900-1500s A.D.) by examining diet, nonspecific stress, and mortality risk using multivariable statistical methods. Delta ^{13}C and $\delta^{15}N$ stable isotope analysis, macroscopic analysis of osteoblastic nonspecific lesions (NSLs), and age-at-death data were collected for 196 monastic and lay individuals from five burial sectors in St. Peter's Monastery cemetery. Binary and multinomial multiple logistic regression were employed to analyze intrapopulation variation. The multivariable analyses reveal that dietary stable isotope values, prevalence and characteristics of nonspecific lesions, and age-at-death varied significantly between Osor's lay and monastic samples and between the various lay burial sectors. Notably, Osor's monastic population's diet significantly differed from that of lay individuals, exhibiting lower $\delta^{15}N$ and higher $\delta^{13}C$ values. Additionally, monastic individuals showed a higher prevalence of nonspecific lesions, with more nonspecific lesions and larger nonspecific lesions than lay individuals. While the presence of nonspecific lesions was associated with older ages-at-death, monastic individuals did not exhibit lower levels of mortality risk. Osor's elite individuals consumed a more protein-rich diet with more marine resources compared to Osor's wider lay population and monastic individuals. These elite individuals displayed greater levels of frailty, evidenced by higher mortality risk and lower nonspecific lesion prevalence, however. Finally, lay individuals from burial sector 6 differed from the wider lay population and exhibited lower $\delta^{15}N$ and $\delta^{13}C$ values and higher average age-at-death, indicating a more terrestrial protein-based diet and lower mortality rates.

4.1 INTRODUCTION

Analyses of nonspecific stress, dietary stable isotopes, and mortality risk are regularly used in bioarchaeological research to assess differences within and between past populations (e.g., Katzenberg & Waters-Rist, 2018; Schrader, 2018; Sofaer, 2006). These analyses are often done discretely, so dietary isotopic data is analyzed separately from evidence of mortality risk or pathological conditions. However, diet, nonspecific stress, and mortality risk are highly interconnected; diet and stress can share a synergistic relationship that can influence mortality risk outcomes (Singer, 2009). Additionally, bioarchaeological data for any one of these factors can impact how we interpret the others (e.g., DeWitte & Stojanowski, 2015; Fuller et al., 2005; Redfern et al., 2019). Here, we use multivariable statistical analyses to simultaneously explore variability within and between monastic and secular members of Osor's medieval (900-1500s A.D.) communities and to assess whether intrapopulation variation within this island sample is comparable to other medieval populations in the region. Together, these data can illuminate layered information about the lived experiences of Osor's monastic and lay communities and how they varied, highlighting the unique character of this medieval island population.

Analysis of nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) stable isotopes from bone collagen provides insight into sources of dietary protein (Katzenberg & Waters-Rist, 2018). With this data, researchers can discern the type of foods individuals were consuming, such as the proportion of marine and terrestrial resources, the amount of high (e.g., tuna) versus low (e.g., oyster) trophic-level foods, and the reliance on plants with different photosynthetic pathways, such as wheat and barley (C_3 plants) or millet (C_4 plants) (Katzenberg & Waters-Rist, 2018; Richards & Hedges, 1999; Schoeninger & DeNiro, 1984).

Nonspecific skeletal lesions (NSLs), such as periosteal new bone formations, do not have one cause and are therefore considered indicators of nonspecific stress (Weston, 2018). The clinical literature suggests that NSL size, distribution, and bone composition can be informative about the timing, intensity, and duration of the condition(s) that result in nonspecific lesions (Bisseret et al., 2015; Ragsdale, 1993; Ragsdale et al., 1981, 2018; Wenaden et al., 2005). They are also some of the most common skeletal pathologies that bioarchaeologists encounter (Buikstra, 2019). Analyzing NSL data alongside age-at-death is essential due to the osteological paradox. (Reitsema & McIlvaine, 2014; Wood et al., 1992).

As a result of heterogeneous frailty and selective mortality, both the presence and absence of NSLs can indicate frailty, defined here as lower resilience to stressors resulting in increased mortality risk (DeWitte & Wood, 2008; Usher, 2000), when correlated with younger ages-at-death or survivorship and resilience when correlated with older ages-at-death (DeWitte & Stojanowski, 2015; Wood et al., 1992). Additionally, DeWitte (2014) demonstrated differences in survival times between individuals with different kinds of NSLs (i.e., active, mixed, or healed). Analyzing NSLs and their characteristics alongside age-at-death data can, therefore, provide valuable information about population health, living conditions, and sociocultural practices (Assis & Keenleyside, 2019; DeWitte, 2014).

In the High Middle Ages (1000–1400s A.D.), the eastern Adriatic coast was a dynamic region characterized by a mix of Slavic, Romanesque, and Venetian cultural influences. Cities in this region often developed distinct identities. Continuous political, social, and economic shifts, including increased urbanization and changes in social structure, characterized this period (Ivetić, 2022; Novak et al., 2012). Conflicts involving Venice, Byzantium, and other regional powers created a backdrop of instability (Ivetić, 2022; Šlaus et al., 2012). Plague outbreaks, notably the Black Death in the fourteenth century, created further crises in this region, impacting population dynamics and health outcomes (Ravančić, 2004).

The Middle Ages were also characterized by significant church reforms throughout Europe. The eastern Adriatic's proximity to Italy made it a significant staging ground for disseminating reformist ideas from Rome across the Adriatic (Gioanni, 2020). From the 900-1000s A.D., there was a notable expansion of Benedictine monasteries throughout the eastern Adriatic, including St. Peter’s Monastery, founded in Osor in the eleventh century, which played a crucial role in reasserting papal authority in this region (Constable, 2017; Frankopan, 2021; Gioanni, 2013; Jurković, 2013). In the Middle Ages, Osor, situated on the Kvarner archipelago in the northern Adriatic (Fig. 4.1), therefore became a center of church reform in the region (Gioanni, 2013).

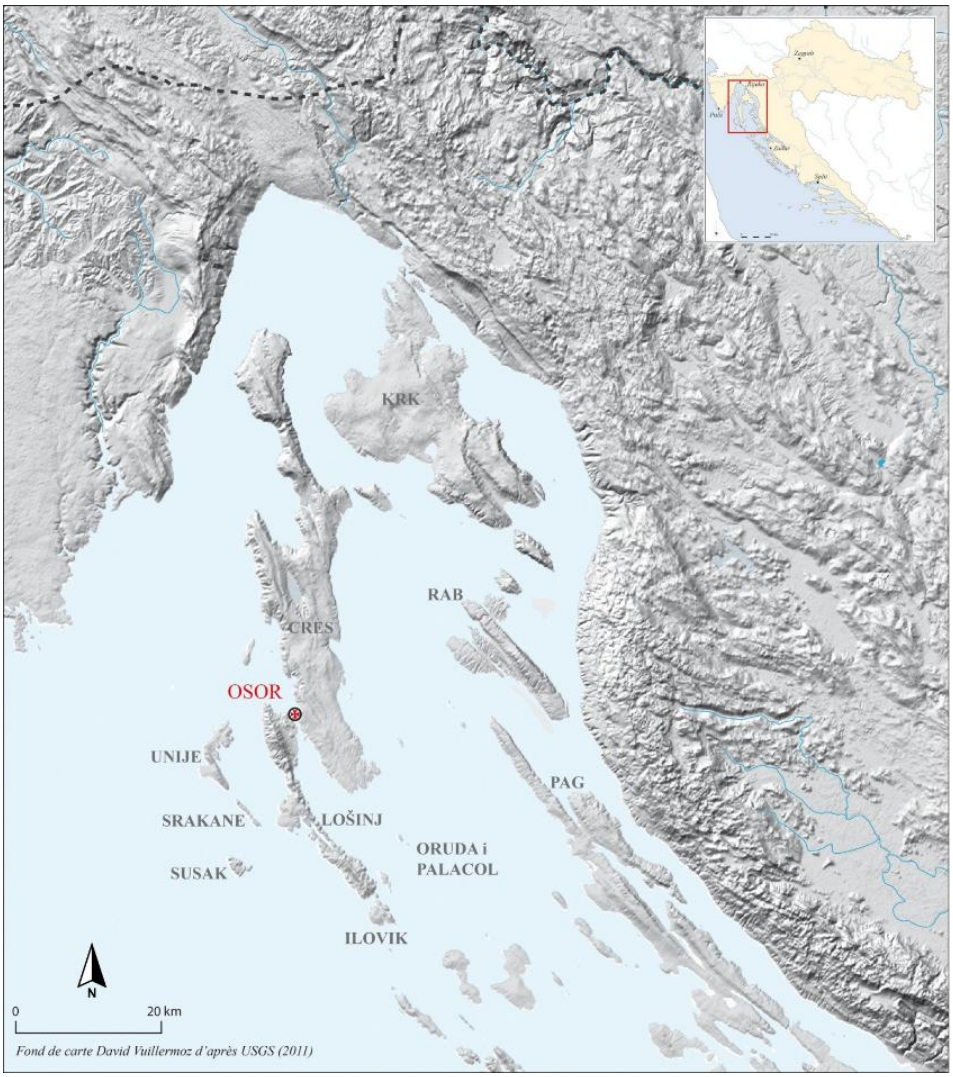

Figure 4.1: Map of Osor (from Čaušević-Bully et al., 2014). Reproduced with permission of M. Čaušević-Bully.

There is a growing body of bioarchaeological research on medieval Croatia examining how medieval populations were impacted by the events of this period. Previous bioarchaeological research suggests that medieval populations in the eastern Adriatic and continental Croatia saw increases in nonspecific stress, mortality, trauma, and dental pathology characteristic of a more carbohydrate-heavy diet, which varied by socioeconomic status and gender (Lightfoot et al., 2012; Novak et al., 2012; Šlaus et al., 2002, 2011, 2012). However, this research largely covers continental and southern Dalmatian populations, and Ivetić (2022) emphasizes the marked differences between coastal and inland populations as well as the multifaceted nature of Adriatic cities. Monastic and lay burials from the medieval St. Peter's cemetery of Osor provide an opportunity to investigate the potential diversity in lived experience across the eastern Adriatic in the Middle Ages and contribute to our knowledge about the lives of religious and secular communities in this region. St. Peter's Monastery contained 551 monastic and lay burials dating to the 900s-1500s A.D. A subset of these burials is examined here to analyze intrapopulation variation in diet, nonspecific stress, and mortality risk between and

within the monastic and lay samples.

4.2 DIET AND HEALTH IN MEDIEVAL MONASTIC AND LAY COMMUNITIES

Benedictine monks lived communally and followed the Rules of St. Benedict, which outlined routines of manual labor, prayer, holy readings, and dietary regulations (Benedict 1975). For diet, the Rule prescribed simple meals, including local, seasonal foods, a pound of bread per person daily, and 0.25 L of wine or ale (Benedict, 1975; Harvey, 1997). Monks were to refrain from eating the quadruped meat, but poultry, eggs, and cheese were allowed (Benedict, 1975). Harvey (1997) notes that, in practice, monastic diets varied according to local circumstances, and different monasteries followed their own rules, which often circumvented the stricter dietary guidelines on meat consumption.

Historical, archaeological, and bioarchaeological data on medieval European communities suggest that monastic diets were often like those of the local elite. That is, they tended to contain more protein, particularly fish (Carić & Novak, 2024; Cirelli, 2013; Harvey, 1997; Janeš & Bedić, 2020; Mays, 2006; Novak, 2013; Rizner, 2017; Živaljević et al., 2019). Stable isotope analysis by Carić & Novak (2024) on a modern (1600-1700s A.D.) community of nuns from Pula, Croatia, attests to marine protein-rich diets in eastern Adriatic religious communities. Novak (2013) further reveals that individuals associated with the Benedictine St. Mihovila monastery in Rudina, Croatia, exhibited osteological indicators of affluent diets (i.e., higher protein), lower rates of nonspecific stress, and older ages-at-death, similar to medieval monastic populations in the UK (e.g., DeWitte, 2024; DeWitte et al., 2013; Marklein et al., 2016; Mays, 1997). Novak (2013) and DeWitte (2024) hypothesize that monastic lifestyles, including a regular diet, access to medical care, daily work regimes, and/or the privileged backgrounds of many monks, accounted for these communities' lower mortality risk. For secular populations, research indicates differences in diet and health in medieval continental populations based on social status and sex, with female and lower-status individuals tending to have less animal protein in their diet and lower ages-at-death than their male and higher-status counterparts (Novak, 2013; Novak et al., 2017; Šlaus, 2000; Šlaus et al., 2007).

Research on diet and subsistence strategies for this region primarily covers the early Middle Ages (600-900s A.D.). Archaeological, historical, and stable isotope data suggest that cultivated grains, including wheat, rye, barley, and millet, were popular staples, as well as cattle, pigs, sheep, goats, and poultry, for early medieval populations in Croatia (Lightfoot et al., 2012). Faunal stable isotope analyses indicates that animal fodder was primarily composed of C_3 plants, with occasional inclusion of C_4 plants (Lightfoot et al., 2012). Coastal populations from this period and/or region often had a fairly terrestrial-based diet despite their proximity to marine environments (Čaušević-Bully et al., 2021, 2023; Lightfoot et al., 2012). Zooarchaeological analyses of faunal remains from the high middle age (1000-1200s A.D.) site of Martinšćica, located ~9km south of Osor, indicates that domestic animals (i.e., goats, cattle, and pigs) likely comprised a large part of this population’s diet, with wild game, fish, and poultry contributing to

a lesser extent (Čaušević-Bully et al., 2021).

4.3 RISE AND DECLINE OF OSOR AND ST. PETER'S MONASTERY

Osor was an important city in the Kvarner region due to its strategic position on a channel linking the western and eastern Adriatic, its administrative role in the Cres-Lošinj archipelago, and its involvement in religious reform during the Middle Ages (Čaušević-Bully et al., 2014). Osor was the seat of the local bishopric from late antiquity (200–600s A.D.) throughout the Middle Ages (Čaušević-Bully et al., 2014). St. Peter's Monastery was a Benedictine monastic complex established in the early eleventh century (~1018 A.D.) by Osor's bishop and St. Peter's first abbot, Gaudentius (Bully et al., 2024; Čaušević-Bully et al., 2014). The monastery reached its peak in the 1000s–1100s A.D. but fell into disrepair by the 1400s A.D., when it was placed under comenda and ceased to house monks (Jurković et al., 2007; Miladinov, 2008; Velčić, 2024). St. Peter's church was then reduced to a smaller church in the 1400-1500s A.D. (Čaušević-Bully et al., 2017).

The decline of St. Peter's Monastery parallels that of Osor. The city experienced a plague outbreak in 1361 (Protić, 2015). Soon after, Genoese forces destroyed Osor during the War of Chioggia (1378-1381 A.D.) between Genoa and Venice (Miladinov, 2008; Protić, 2015). Protić (2015) reports that soon afterward, an outbreak of malaria, which had traditionally afflicted much of Dalmatia and the northern Adriatic (Novak et al., 2012; Novak, Milošević, et al., 2021), further reduced the number of Osor's inhabitants. The city had also begun to lose its strategic importance in the fifteenth century as advancements allowed for better open sea navigation, diminishing the need for sailing routes that followed the safe harbors of the Adriatic islands (Mlacović, 2012; Protić, 2015). By the fifteenth century, the eastern half of Osor had been abandoned (Čaušević-Bully et al., 2017; Miladinov, 2008).

St. Peter's cemeteries were established with the monastic complex. The monastic cemetery, located south of the Church, was primarily in use during the monastery's peak in the 1000-1200s A.D. (Bully et al., 2024). Concurrently, a lay cemetery was established behind the church's apse in the eleventh century (Bully et al., 2024). Over time, the lay cemetery expanded, extending north of St. Peter's church (1100–1400s A.D.) and into the church itself (1200–1500s A.D.). With the decline of the monastery, the monastic mausoleum was demolished, and the monastic cemetery covered. This area was subsequently incorporated into the lay cemetery by the 1400s A.D. (Marić et al., 2014). The monastic cemetery, therefore, predates many of Osor's later historical disruptions. In contrast, the lay cemetery remained in use both before and after the turbulent fourteenth and fifteenth centuries, with burials within the church more confined to that period.

4.4 ST. PETER'S CEMETERY

St. Peter's Monastery was excavated from 2006 to 2017 in a partnership between the International Centre for Research on Late Antiquity, the Middle Ages of Zagreb-Motovun (University of Zagreb), UMR 5594 ARTeHIS of the Centre Nationale de Recherche Scientifique (CNRS) (Dijon, France), Ecole française de Rome (Rome, Italy), and the Unité Mixte de Recherche (UMR) Chrono-environnement (Besançon, France). A total of 551 burials were excavated between the two cemeteries, which spanned five separate burial sectors (Fig. 4.2). Basic, non-privileged internments generally consisted of soil and coffin burials with no grave goods. Privileged burials were characterized by stone burials (e.g., masonry tombs, slab burials, vault tombs) and, in some cases, the presence of grave goods (Bully et al., 2024). Stone tombs were often used for multiple internments, and the lay cemetery contained overlapping burials (Bully et al., 2009, 2017; Čaušević-Bully et al., 2017). Individual skeletons were differentiated through careful excavation and onsite osteological examination. Commingled remains were not included in this study.

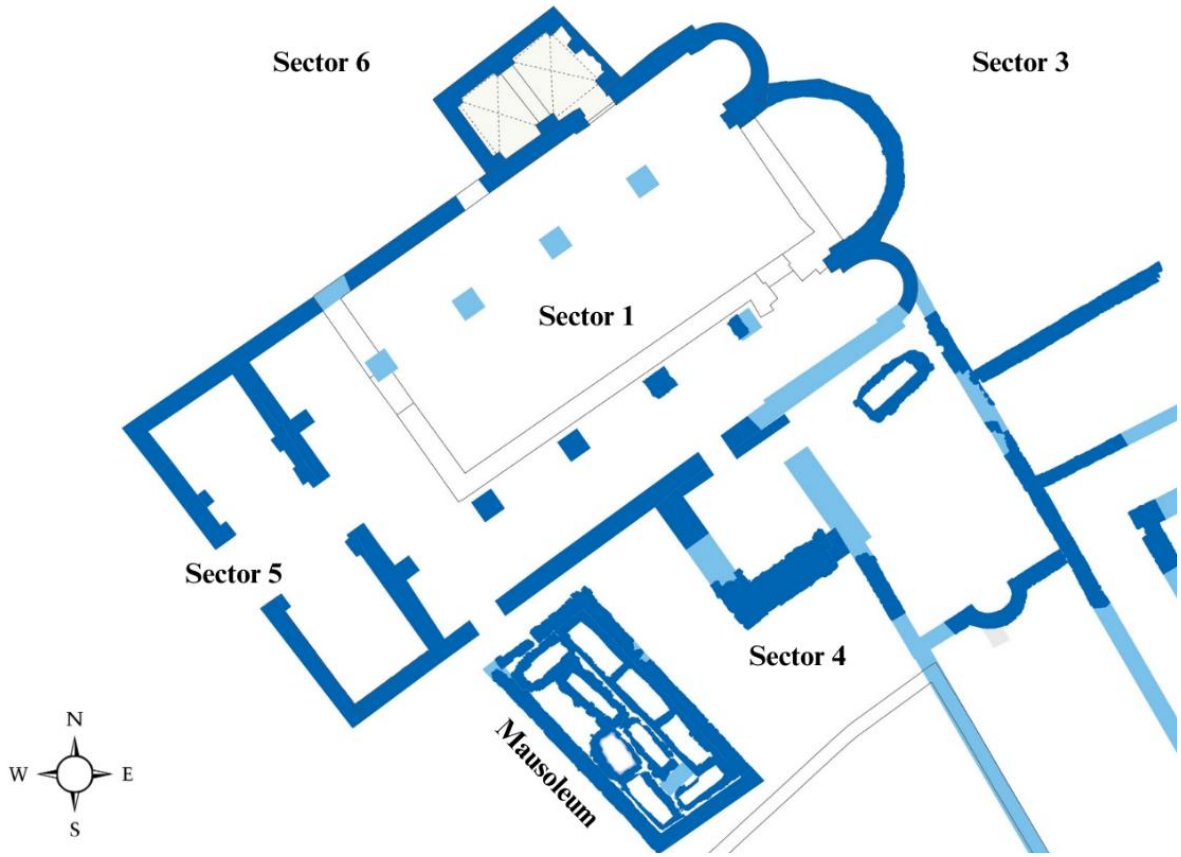

Figure 4.2: Plan of St. Peter's cemetery. Note that the monastic cemetery (including the mausoleum) and lay sector 4 are both in "Sector 4" with lay century burials located stratigraphically above the earlier monastic burials. Modified with permission of M. Čaušević-Bully.

The monastic burials (1000-1200s A.D.) were distinguishable archaeologically based on their location in Sector 4, the consistent use of masonry tombs in this sector, and the predominance of male burials (i.e., 85%; Table 4.2). This cemetery is located stratigraphically beneath later lay burials on the south side of the church and is designated as Sector 4M (i.e., Sector 4 Monastic) in the analysis (Fig. 4.2). Radiocarbon dating of the monastic cemetery's mausoleum suggests some of the earliest burials predate St. Peter's monastery and were likely linked to an earlier church or local elite (Bully, 2014; Marić et al., 2014). Additionally, some mausoleum tombs contained female burials (n=9), which Bully et al. (2024) suggest might belong to high-status individuals or nuns from the nearby female St. Mary of the Angels monastery. Excepting these burials, burials within and outside the mausoleum from the eleventh century onwards were exclusively male, testifying to their monastic nature (Bully et al., 2024).

The lay cemetery was distinguished by overlapping burials, the presence of women and children, and chronology. This cemetery spans Sectors 1, 3, 4, 5, and 6 and burials primarily date to the 1200s-1400s A.D., but range from the 1000-1500s A.D. (Table 4.1; Bully et al., 2008; Čaušević-Bully et al., 2017; Marić et al., 2014). Medieval burials were typically simple, but placement within the cemetery often reflected social status or lineage (O'Sullivan, 2013). Sectors 1 and 5, located within and just outside St. Peter's church (Fig. 4.2), were privileged burial areas likely reserved for Osor's elite and clergy (Bully et al., 2015; Čaušević-Bully et al., 2017). All burials in these sectors are, therefore, considered "privileged". Burials in Sectors 3, 4, and 6 are identified as "basic" unless otherwise distinguishable by burial type or grave goods. Sector 3 (1000-1400s A.D.), located behind the church's apse, contains basic and privileged burials. Its location and burials with high-status burial goods, such as spurs, suggests that this was likely another burial location for Osor's local aristocracy (Čaušević-Bully et al., 2011). The presence of eleventh-century burials and a higher ratio of males in Sector 3 (Table 4.2) suggests that some individuals may have been associated with the early monastic complex (Čaušević-Bully et al., 2014; Marić et al., 2010). However, burial type, burial goods, and the inclusion of women and children suggest that most burials represent the lay population. Nevertheless, this was controlled for in the analysis (see below). To the south, use of Sector 4 for basic lay burials began after the demolition of the mausoleum (1200-1300s A.D.) and continued into the modern era following the reduction of the church (1400-1500 A.D.; Marić et al., 2014). To the north, Sector 6 (1100-1400s A.D.) includes a mix of basic and privileged burials (Bully et al., 2008; Marić et al., 2014).

Table 4.1: Summary of burial sectors' sample size, chronology, location relative to St. Peter's church, and burial types.

Descriptives				
Sector	**N**	**Chronology**	**Location**	**Burial Types**
1	13	13^{th}-16^{th}	Church Nave	Privileged
3	28	11^{th}-15^{th}	East of Church	Mixed
4 (Lay)	26	15^{th} – 16^{th}	South of Church	Basic
4 (Monastic)	78	11^{th} – 13^{th}	South of Church	Monastic
5	16	13^{th}-15^{th}	Church Vestibule	Privileged
6	35	12^{th}-15^{th}	North of Church	Mixed
Total	196			

Table 4.2: Sex estimation by burial sector

Sector	**Female**		**Male**		**Ambiguous**		**Total**
	N	**%**	**N**	**%**	**N**	**%**	**Count**
1	8	62.0	5	38.0	-	-	13
3	5	18.0	20	71.0	3	11.0	28
4 (Lay)	7	27.0	19	73.0	-	-	26
4 (Monastic)	9	12.0	66	85.0	3	3.0	78
5	6	38.0	9	56.0	1	6.0	16
6	12	34.3	18	51.4	5	14.3	35
Total	47	24.0	137	70.0	12	6.0	196

We hypothesize that Osor's cemetery sample will resemble other contemporaneous Croatian monastic and lay communities; that is, monastic individuals consumed an elite diet (i.e., more protein-rich diet), had longer life spans, and exhibited patterns of nonspecific stress indicative of survivorship and resilience. For the lay population, we hypothesize that privileged individuals in Sectors 1 and 5 had more protein-rich diets, longer life spans, and will exhibit nonspecific stress patterns indicative of resilience. Non-privileged individuals are hypothesized to have less protein-rich diets, patterns of nonspecific stress indicative of greater frailty, and higher rates of mortality.

4.5 MATERIALS AND METHODS

A sample of 196 well-preserved individuals (i.e., all skeletal elements analyzed were "present") was selected for multivariable analysis. Only adults and adolescents whose long bones

had begun to fuse (i.e., ≥ 14 years) were included, as the relationship between diet, nonspecific stress, and mortality in infants and young children requires separate analysis.

The sample was divided by cemetery (i.e., monastic and lay) and burial sector for analysis. Although some overlap may exist, archaeological evidence suggests that most individuals belong to monastic (n = 78) or lay (n = 118) groups, respectively. Data analysis was conducted with and without the monastic female and Sector 3 burials to ensure that possible admixture didn't impact the results. Age-at-death was estimated using Transition Analysis 2 (TA2), a multifactorial age-estimation method, scoring the features of the pubic symphysis and auricular surface. The maximum likelihood age estimates were used for statistical analysis (Boldsen et al., 2002). Timing of epiphyseal fusion by Cardoso (2008a, 2008b) was used to estimate the age of individuals with partial long bone fusion (Fig. 4.3). Sex was estimated using the traits outlined in (Buikstra & Ubelaker, 1994) for os coxae and crania (Table 4.2; Acsádi & Nemeskéri, 1970; Milner, 1992; Phenice, 1969). Sex-based differences are not the focus of this analysis; however, Novak et al. (2021) and Šlaus (2000) show significant differences by sex in this region and period. The data are therefore reported by sex to facilitate comparisons and control for these differences in the analysis.

Faunal remains from St. Peter's Monastery were recovered from grave fill, but their chronological relationship to the osteological sample is uncertain. Therefore, faunal remains (n=20) from a neighboring coastal medieval site (1000-1200s A.D.) in Martinšćica, Cres, were used as a proxy for faunal stable isotope values (Čaušević-Bully et al., 2021).

4.5.i Analysis of Nonspecific Lesions

A macroscopic paleopathological analysis recorded osteoblastic (e.g., periosteal new bone formations) nonspecific lesions (NSLs) on long bones, recording their presence or absence, bone composition (lamellar, woven, or mixed), number per individual, number of affected bones, and maximum extent across bone regions (e.g., diaphysis and metaphysis, proximal to distal shaft). Areas of periosteal new bone growth surrounded by normal bone were recorded as a single lesion. Articular surfaces were not observed, and NSLs associated with fractures, entheseal changes, and osteoarthritis were excluded.

To account for preservation bias, each bone analyzed was scored for abrasion/erosion on a scale of 0 to 5+ following McKinley (2004), and an average abrasion/erosion score was calculated for each individual. Each bone and individual was scored for Anatomical Preservation Index (API) class on a scale of 1 (0% bone preserved) to 6 (100% bone preserved) following Bello et al. (2006) based on Dutour (1989). Long bones were considered "present" when at least 50% of the bone was preserved (i.e., API ≥ 4).

4.5.ii Stable Isotope Analysis

Rib samples from 179/196 individuals were analyzed to reconstruct diet 5–7 years before death, based on estimated rib turnover rates (Cox & Sealy, 1997; Fahy et al., 2017). Collagen extraction followed the Longin (1971) and Chisholm et al. (1982) protocols. The bone samples were demineralized in a series of 0.25M HCl (hydrochloric acid) washes, rinsed 3x in H_20, and washed in 0.1M NaOH (sodium hydroxide) to remove base-soluble contaminants. After further H_20 rinses, the samples were heated in a 0.001M HCl solution at 80°C for 24 hours twice. The hot water-soluble collagen was then isolated and dried in a 60°C oven. Unpublished stable isotope data from 17/40 human rib collagen samples analyzed at the Institute for Anthropological Research (Zagreb, Croatia) were incorporated into this study (final n=196). Of these, 12 samples were rerun to ensure that different lab procedures did not produce significantly different results (Tables S4.9, S4.10).

Twenty faunal samples from sheep (n=3), goats (n=4), equids (n=3), pigs (n=4), cattle (n=3), and canines (n=3) were analyzed (Table S4.2). Due to commingling, the exact number of animals this represents is unknown. Fish samples were unavailable, but they were likely part of the diet. Stable isotope data from historically documented marine species were therefore used—prioritizing medieval Mediterranean sources, and supplementing with modern Mediterranean and Adriatic data when necessary (Alexander et al., 2015; Fanelli et al., 2023; Garcia-Guixé et al., 2010; Gismondi et al., 2020; Mion et al., 2022; Navarro et al., 2013; Zorica et al., 2021).

Prepared collagen samples were sent to the Jan Vizier lab in Ottawa for stable isotope analysis. Samples and standards were weighed into tin capsules and loaded into an elemental analyzer interfaced with a Delta Advantage isotope ratio mass spectrometer. All $\delta^{15}N$ data are reported in ‰ (per mil) vs. AIR. All $\delta^{13}C$ data are reported in ‰ VPDB. Repeated measures with internal standards (C-55 – L-glutamic acid) resulted in a standard error of 0.1‰ for both carbon and nitrogen. C:N ratios and %C and %N were examined to ensure adequate quality, specifically %C > 14.0% and %N > 4.8% (Ambrose, 1990). A slightly more conservative C:N ratio of 2.9 - 3.5 was used following Guiry & Szpak (2021). See Supplementary File 2 for quality control information.

4.5.iii Statistical Analysis

Despite good preservation, some of the n=196 in this study still had missing data (Table 4.3). Missing data were imputed using IBM SPSS Statistics, following Wissler et al. (2022a, 2022b). A Missing Completely at Random (MCAR) test confirmed that missing data was randomly distributed (Table S4.1). Estimated-Maximization (EM), a maximum likelihood method, was employed to impute missing data.

Table 4.3: Percentage (%) of data missing by independent variable. Independent variables not listed had no missing data.

Variable	N	% Missing
Age-at-Death	7	4.0
Sex Estimation	5	2.5
$\delta^{13}C$	2	1.0
$\delta^{15}N$	2	1.0

All other statistical analyses were done using the open-source software Jamovi. Binary logistic regression was used to compare the monastic and lay cemeteries, and multinomial logistic regression to compare burial sectors. Logistic regression is a statistical method for modeling the conditional or relative probability of belonging to one category versus another (i.e., monastic vs. lay) based on predictor (i.e., independent) variables (Menard, 2010). This method has the advantage of allowing researchers to incorporate non-normally distributed and heteroscedastic data, multiple types of data (i.e., categorical and continuous), control for the influence of predictor variables on each other, include interaction terms, and does not assume a linear relationship between the predictor and dependent variables.

An overall model test and Akaike's Information Criterion (AIC) were used to measure the model's fit (Menard, 2010). Backward elimination was used where all variables of interest were entered into the regression model, and variables whose p-value was > α=0.10 were sequentially removed until only those with p-values ≤ 0.10 remained (Menard, 2010). Each model included $\delta^{13}C$, $\delta^{15}N$, age-at-death, NSL absence/presence, NSL number, number of bones affected, NSL size, estimated sex, and two-way interactions between all variables as independent variables. Interaction terms were only kept if they did not negatively impact the model's fit. Z-score transformations were used to standardize continuous variables to aid interpretation(Menard, 2010). Individuals with significant outlying deviance residuals (i.e., z-score > 3.5) were filtered out for binary logistic regression.

Due to the inherent correlations between the NSL data, only one to two paleopathological variables could be retained in the logistic regression analysis without violating assumptions of non-multicollinearity. Consequently, chi-squared tests, t-tests, and ANOVAs were used to supplement these analyses. Non-parametric tests were used for non-normally distributed data. Chi-squared tests, t-tests, and Spearman's correlation were used to examine the relationship between dietary stable isotopes and nonspecific stress with an $\alpha = 0.05$. The effects of cemetery, burial sector, and NSL presence on survival were assessed using Kaplan-Meier survival analyses with a Tarone-Ware test of significance.

4.6 RESULTS

Erosion/abrasion across the sample was slight to moderate (average grade = 1.6; patchy surface erosion). A chi-squared analysis found no significant association between abrasion/erosion grades and NSL presence ($p = 0.473$), suggesting that taphonomic damage did not affect the paleopathological data (Table S4.2). All stable isotope samples met quality control standards for collagen yields, %C, %N, and C:N ratios (Tables S4.11, S4.12).

The average age-at-death for the sample was 47.4 (+/- 18.9) years (Table 4.4), with peaks at 25-29 and 65-69 years. Figure 4.3 illustrates differences in age distributions across burial sectors. The lay cemetery had a greater proportion of individuals in the younger (20-30 years) and older (70+ years) age groups. Kaplan-Meier analyses reveal no significant differences in survivorship between lay and monastic individuals ($p = 0.698$) but do demonstrate a trend of increased survivorship for lay individuals aged 60 years and older (Table S4.5; Fig. S4.1). The age-at-death distributions trended younger for Sectors 1, 3, and 5. Kaplan-Meier analyses confirm significantly lower median survival times for these individuals ($p = < 0.001$; Table S4.6 and Fig. S4.2).

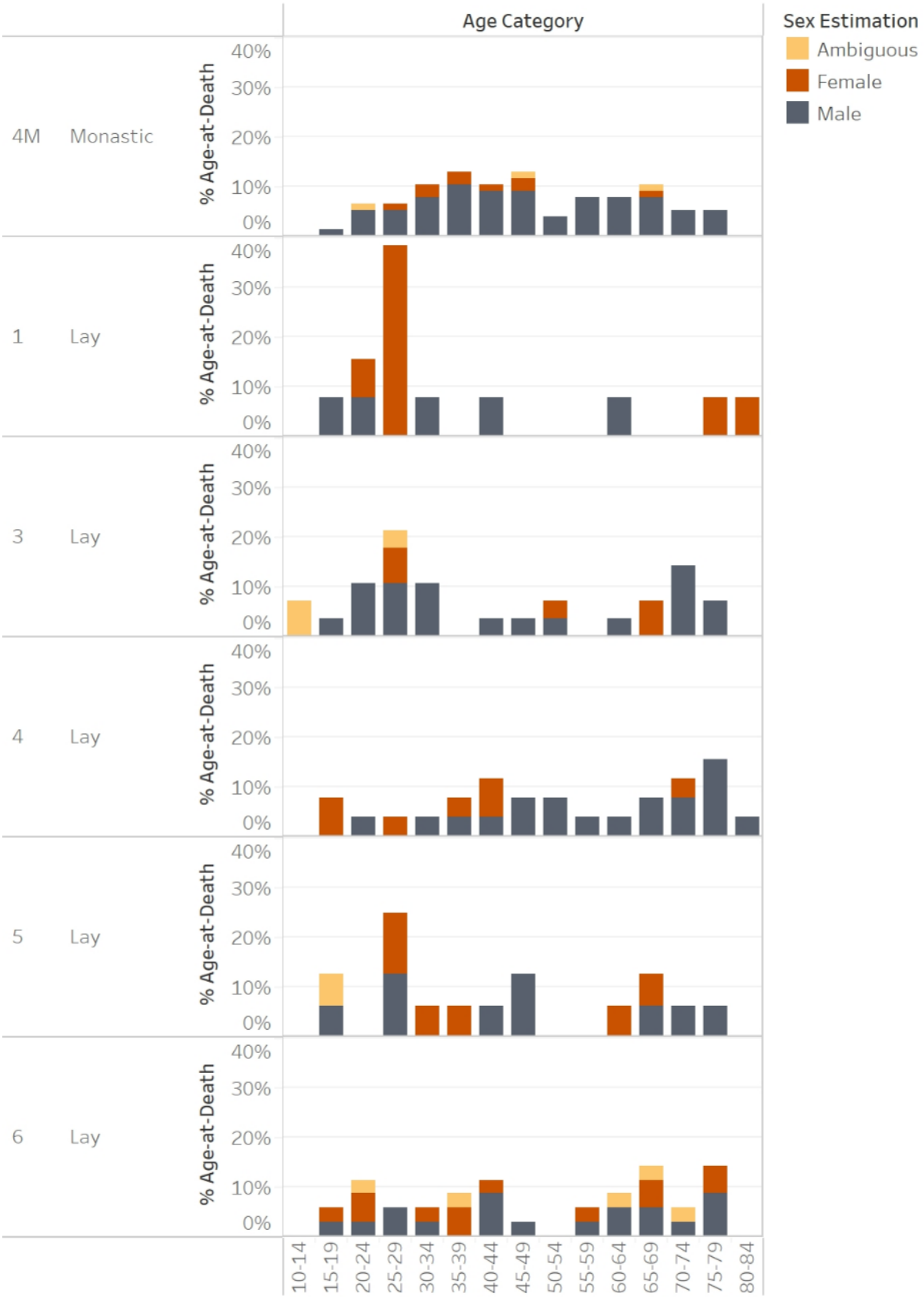

Figure 4.3: Age-at-death distribution by cemetery and burial sector for the full (n=341) sample.

Table 4.4: Age-at-death summary data

Group	N	Mean Age-at-Death (Yrs)	Median Ages-at-Death (Yrs)	SD
All	196	47.4	44.9	18.9
Category				
Monastic	78	47.8	45.8	16.0
Lay	118	47.3	44.4	20.0
Sector				
1	13	38.5	27.4	21.9
3	28	44.2	36.8	21.5
4 (Lay)	26	53.3	52.4	19.8
5	16	43.4	39.3	19.3
6	35	50.3	46.1	19.7
Sex				
Male	137	49.8	46.9	18.2
Female	47	42.7	38.3	19.2
Ambiguous	12	39.4	32.4	21.8

For human samples, stable isotopes ranged from: $\delta^{13}C$ = -19.9 to -17.3 ± 0.1‰ (mean -18.7 ± 0.4‰) and $\delta^{15}N$ = 8.3 to 12.4 ± 0.1‰ (mean 10.7 ± 0.7‰). Table 4.5 presents the stable isotope data by cemetery, burial sector, and estimated sex. Figure 4.4 presents the average human, Martinšćica faunal, and published marine species values (Alexander et al., 2015; Fanelli et al., 2023; Garcia-Guixé et al., 2010; Gismondi et al., 2020; Mion et al., 2022; Navarro et al., 2013; Zorica et al., 2021). Bone collagen $\delta^{13}C$ values are ~5‰ higher than those of the diet (Katzenberg & Waters-Rist, 2018). For $\delta^{15}N$, a trophic level effect increases $\delta^{15}N$ by 3-5‰ per trophic step, as well as ~1.0‰ for $\delta^{13}C$ (Hedges & Reynard, 2007). Osor's average $\delta^{15}N$ value is ~5‰ higher than the terrestrial faunal species analyzed, excluding canines. The average human values exceed those of lower trophic marine organisms (e.g., oysters, anchovies, sardines) by 0.3 to 2.3‰ for $\delta^{13}C$ and 1.0 to 6.2‰ for $\delta^{15}N$. In contrast, higher-trophic marine species (e.g., tuna and mullet) had greater mean values than humans.

Figure 4.4: Average $\delta^{13}C$ and $\delta^{15}N$ values presented by species. Average human values represent the mean for the entire Osor sample.

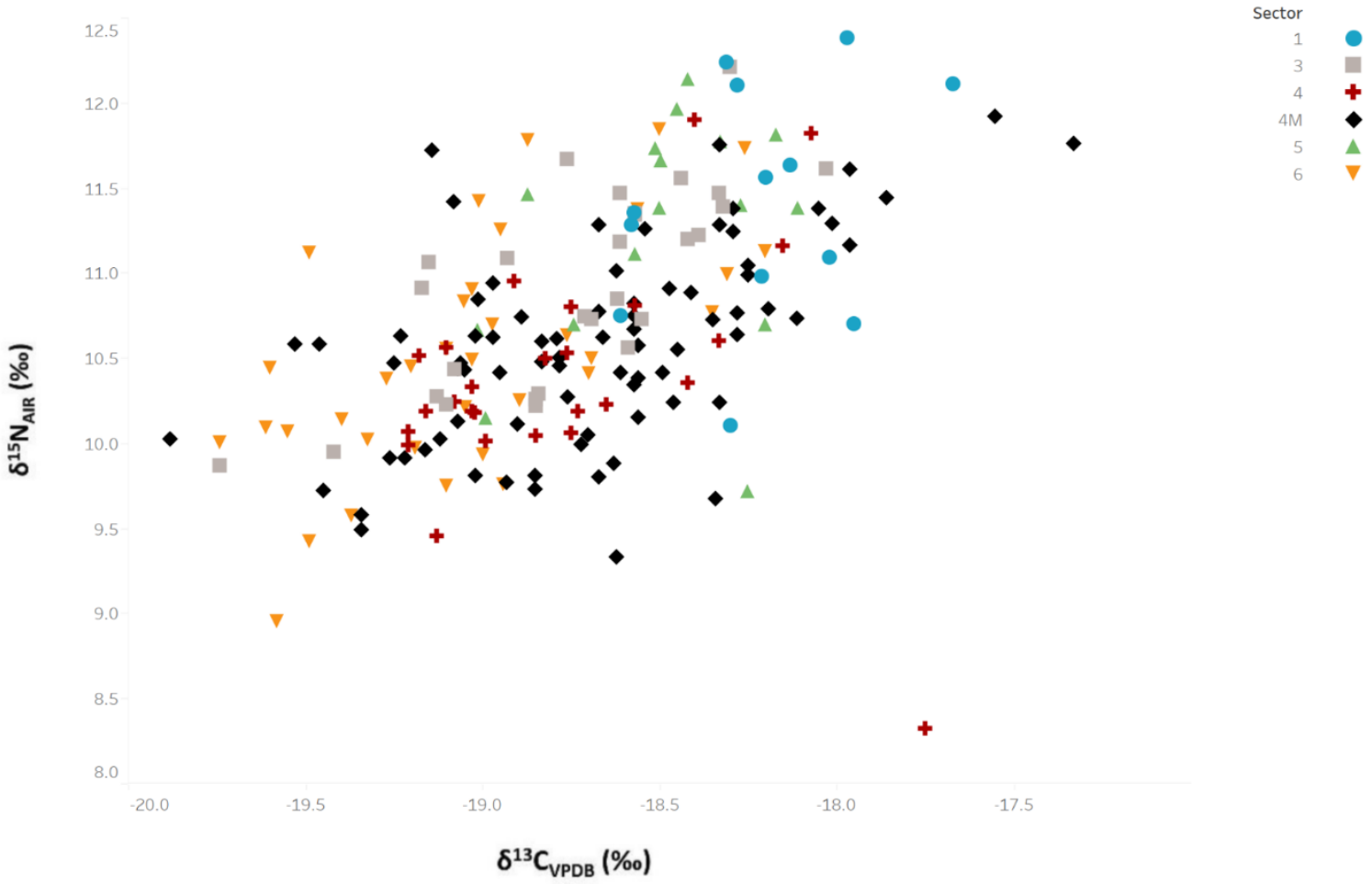

Figure 4.5: $\delta^{13}C$ and $\delta^{15}N$ distinguished by burial sector. Sector 4M refers to the monastic burials.

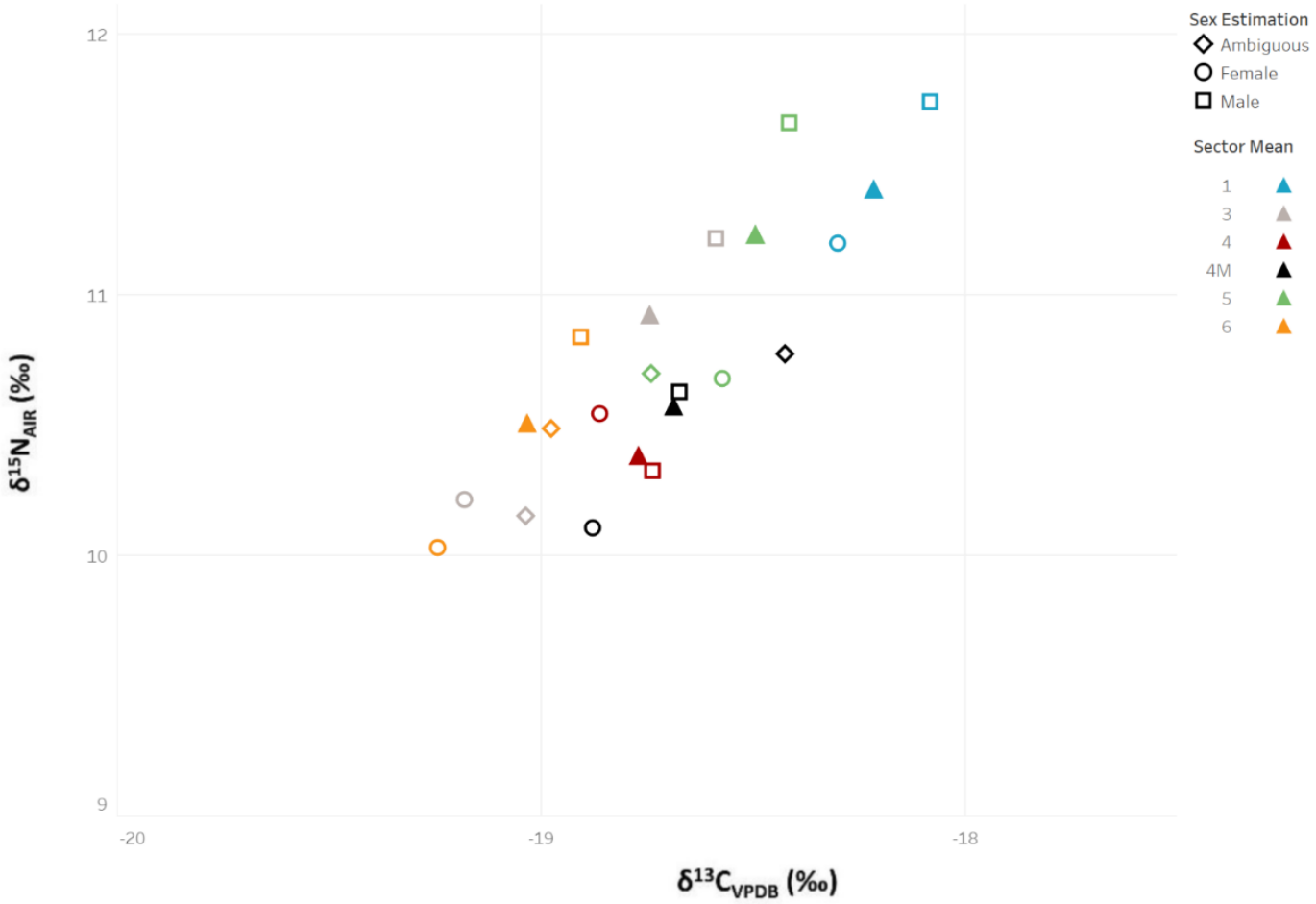

Figure 4.6: Average $\delta^{13}C$ and $\delta^{15}N$ values for each burial sector broken down by sex estimation. Sector 4M refers to the monastic burials. The solid triangles indicate the mean value for the entire burial sector (i.e., males, females, and ambiguous individuals grouped together).

Table 4.5: Stable isotope summary data

	$\delta^{13}C$ (‰) VPDB			$\delta^{15}N$ (‰) (AIR)		
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**
All	-18.7	0.4	2.6	10.7	0.7	4.1
Category						
Monastic	-18.7	0.5	2.6	10.6	0.6	3
Lay	-18.7	0.4	2.1	10.8	0.7	4
Sector						
1	-18.2	0.3	1.0	11.4	0.6	1.8
3	-18.7	0.4	1.7	10.9	0.6	2.3
4 (Lay)	-18.8	0.4	1.5	10.4	0.7	3.6
5	-18.5	0.3	0.9	11.2	0.7	2.4
6	-19.0	0.4	1.5	10.5	0.7	2.9
Sex						
Male	-18.7	0.4	2.6	10.8	0.7	3.9
Female	-18.9	0.5	1.8	10.4	0.7	3.4
Ambiguous	-18.8	0.5	1.6	10.5	0.7	2.3

Figures 4.5 and 4.6 present the isotope data by cemetery, burial sector, and estimated sex. Sectors 1 and 5 have some of the highest $\delta^{13}C$ and $\delta^{15}N$ values in the sample, while Sectors 4 (lay) and 6 have the lowest. The monastic cemetery's average $\delta^{15}N$ and $\delta^{13}C$ values aligned more closely with lay Sectors 4 and 6. Sector 3's average values, especially the males, were closer to those of Sectors 1 and 5 (privileged) than the monastic group (Sector 4M). Figure 4.6 shows that female and ambiguous individuals consistently had lower values than males.

Paleopathological analysis reveals that 64.8% (n=127/196) of individuals exhibited nonspecific lesions (NSLs) on their long bones (Table 4.6). Among the lay burial sectors, Sectors 3 and 5 had a markedly lower prevalence of NSLs than the other sectors. These lesions were generally comprised of lamellar bone (68.5%). Individuals with NSLs had a mean of 2.3 long bones affected, 3 NSLs, and these NSLs extended across 1.5 regions of the bone (Table 4.7). Monastic individuals, males, and lay Sector 4 individuals had a greater prevalence of NSLs, more NSLs, and larger NSLs than their counterparts.

Table 4.6: Prevalence (%) of nonspecific lesions and bone composition by cemetery, burial sector, and estimated sex. 'All' refers to the full combined sample. For estimated sex: 'M' = male, 'F' = female, and 'A' = ambiguous."

		All	Cemetery		Sector					Sex		
			Mon.	Lay	1	3	4 (Lay)	5	6	M	F	A
Prevalence (%)		64.8	74.4	58.5	69.2	46.4	65.4	37.5	68.6	70.8	48.9	58.3
Bone Composition (%)	Lamellar	68.5	65.6	71.0	66.7	76.9	64.7	83.3	70.8	69.1	69.6	57.1
	Woven	2.4	3.4	1.4	0	0	5.9	0	0	3.1	0	0
	Mixed	29.1	31	27.5	33.3	23.1	29.4	16.7	29.2	27.8	30.4	42.9

Table 4.7: Average values of nonspecific lesion number, bones affected, and maximum nonspecific lesion size by cemetery, burial sector, and estimated sex. 'All' refers to the full combined sample. For estimated sex: 'M' = male, 'F' = female, and 'A' = ambiguous."

Variable	All	Cemetery		Sector					Sex		
		Monastic	Lay	1	3	4 (Lay)	5	6	M	F	A
NSL Number	3.0	3.5	2.6	2.7	2.5	3.9	2.2	2.0	3.4	1.7	3.3
Bones Affected	2.3	2.4	2.2	2.4	2.0	2.9	2.2	1.8	2.5	1.7	2.3
NSL Size	1.5	1.7	1.3	1.7	1.2	1.4	1.5	1.2	1.6	1.2	1.4

4.6.i Relationships between Diet, Nonspecific Stress, and Mortality

These tests aimed to identify correlations between NSL presence, age-at-death, and dietary isotopes, so only NSL presence was analyzed. Spearman's correlation revealed a statistically significant, negative correlation between age-at-death and $\delta^{15}N$ values (Spearman's r: -0.212; p = 0.003), but not $\delta^{13}C$ values (Spearman's r: -0.06, p = 0.372; Table S4.3). For NSL presence, the Kaplan-Meier survival analysis indicates significantly greater median survival times for individuals with NSLs (median difference = 7.2 yrs, p = 0.002; Table S4.7, Fig. S4.3). T-tests suggest no correlation between NSL presence and $\delta^{13}C$ (p = 0.879) and $\delta^{15}N$ values (p = 0.293; Table S4.4).

4.6.ii Monastic and Lay Cemeteries

Binary logistic regression identified variables that significantly distinguished monastic from lay burials. Two individuals with significant outlying deviance residuals were filtered out. The overall model is statistically significant ($\chi^2 = 69.1$, $p < 0.001$), confirming that it explains variation better than no predictors. McFadden's R^2 of 0.27 indicates a well-fitting model that explains 27% of the variance in the data (McFadden, 1973). Filtering out groups that may skew the analysis (e.g., monastic females and Sector 3 burials) did not change the results, so they were retained. The model indicates that $\delta^{13}C$ values, $\delta^{15}N$ values, age-at-death, estimated sex, NSL size, and interactions between $\delta^{15}N$ values and NSL number and NSL size were significant predictors (Table 4.8).

Table 4.8: Results of the binary multiple logistic regression. For sex estimation, males were set as the reference group, so all categories are compared against this. In the results, "✻" denotes an interaction term. The monastic sample size is n=78, and the lay sample size is n=118.

				Overall Model Test		
Model	**Deviance**	**AIC**	**R^2_{McF}**	**χ^2**	**df**	**p**
1	191	209	0.266	69.1	8	< .001

					95% Confidence Interval	
Predictor	**Estimate**	**SE**	**p**	**Odds Ratio**	**Lower**	**Upper**
Intercept	-0.12	0.21	0.561	0.89	0.59	1.33
Age-at-Death	0.47	0.20	0.019	1.60	1.08	2.37
$\delta^{15}N$	1.18	0.26	< .001	3.25	1.94	5.42
$\delta^{13}C$	-0.61	0.22	0.006	0.54	0.35	0.84
Sex Estimation:						
Ambiguous vs. Male	2.05	0.89	0.021	7.77	1.37	44.17
Female vs. Male	2.32	0.54	< .001	10.14	3.49	29.43
NSL Size	-0.55	0.20	0.007	0.58	0.39	0.86
$\delta^{15}N$ ✻ NSL Number	-1.55	0.40	< .001	0.21	0.10	0.47
NSL Size ✻ $\delta^{15}N$	1.21	0.40	0.002	3.37	1.54	7.35

Note. Estimates represent the log odds of "Cemetery = 1" vs. "Cemetery = 0"

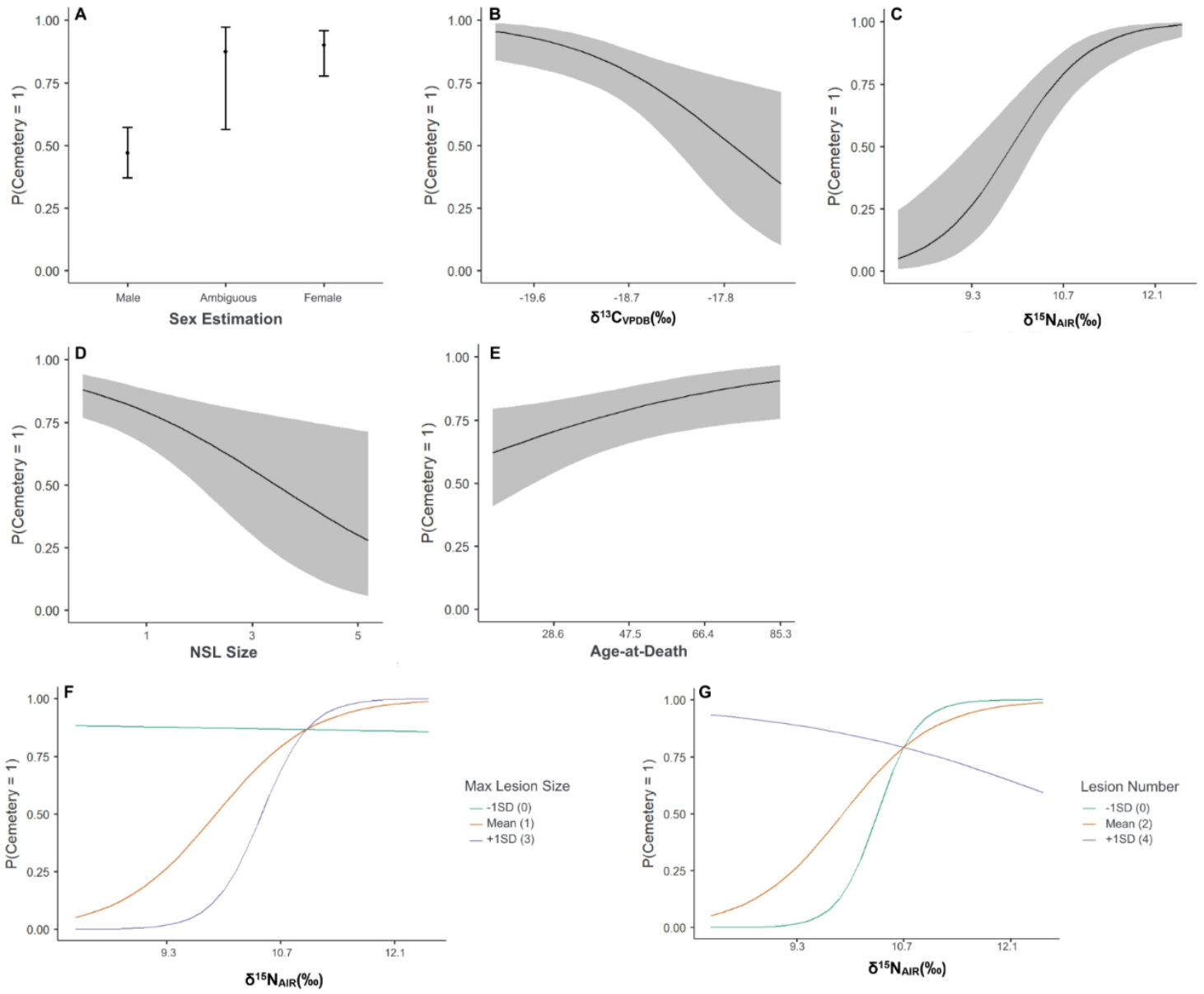

Figure 4.7: Estimated marginal mean (EMM) plots for the binary logistic regression results. The plots illustrate the relationship between the probability of belonging to the monastic (i.e., 0) or lay (i.e., 1) cemetery based on the value of the predictor variable, including: A) estimated sex, B) $\delta^{13}C$ values, C) $\delta^{15}N$ values, D) NSL size represented by the number of bone regions an NSL extended across, E) age-at-death, F) $\delta^{15}N$ values based on NSL size [interaction term], G) $\delta^{15}N$ values based on the number of NSLs an individual had [interaction term].

With 85% of monastic burials being male, an estimated female sex significantly increases the odds of being a lay burial (OR = 10.14, 95% CI = 3.5–29.4; Fig. 4.7a). A one-unit increase in $\delta^{15}N$ (0.7‰) and $\delta^{13}C$ (0.4‰) values were associated with an increase in the odds (OR: 3.2, 95% CI: 1.9-5.4) of coming from the lay cemetery for $\delta^{15}N$ and a decrease in the odds (OR: 0.54, 95% CI: 0.35–0.84) for $\delta^{13}C$ (Figs. 4.7b and 4.7c). This suggests that individuals from the lay cemetery tended to have higher $\delta^{15}N$ and lower $\delta^{13}C$ values. Figures 4.7b and 4.7c indicate that

individuals with $\delta^{15}N$ values of ≥ 10.7‰ and $\delta^{13}C$ values ≤ -18.7‰ were likelier to be from the lay cemetery when the other predictors are held constant. The increasing confidence interval at the highest $\delta^{13}C$ values is likely due to overlap and a small number of individuals with $\delta^{13}C$ values at the uppermost range.

An increase in NSL size decreases the odds (OR: 0.58, 95% CI: 0.39–0.86) of coming from the lay cemetery, indicating that monastic individuals tended to have larger NSLs. Individuals with NSLs extending over 3+ regions of the bone are likelier to be from the monastic cemetery (Fig. 4.7d). The significant increase in the confidence interval at the upper end of NSL Size is likely the result of a small number of individuals having NSLs that extended across 4+ regions of their long bones (n=2). Table 4.9 presents the supplemental chi-squared and t-test results for the paleopathological variables that could not be included in the logistic regression analysis. The monastic cemetery had a significantly greater proportion of individuals with NSLs ($p = .023$; 74.4% vs. 58.5%). There were no significant differences for NSL bone composition ($p = 0.669$), NSLs number ($p = 0.11$), or the number of bones with NSLs ($p = .521$) between these two groups.

Table 4.9: Results of the supplemental bivariate analyses of the paleopathological data comparing cemeteries (monastic vs. lay) and burial sectors (lay burial sectors 1, 3, 4, 5, and 6). Statistically significant results ($\alpha = .05$) are bolded.

Group	Test	Variable	Statistic/Value	P
Monastic vs. Lay Cemetery	Chi-squared (X^2)	NSL Prevalence	5.19	0.023
	Chi-squared (X^2)	NSL Bone Type	0.804	0.669
	Mann-Whitney U t-Test	NSL Number	1680	0.111
	Mann-Whitney U t-Test	NSL Bones Affected	1873	0.521
Burial Sector	Chi-squared (X^2)	NSL Prevalence	7.17	0.130
	Chi-squared (X^2)	NSL Bone Type	3.88	0.870
	Kruskal-Wallis ANOVA	NSL Number	7.84	0.098
	Kruskal-Wallis ANOVA	NSL Bones Affected	6.28	0.180

The likelihood that an individual belonged to the monastic or lay cemetery based on δ^{15N} varies with NSL size and number. This indicates that monastic individuals with more and larger NSLs were likelier to have higher $\delta^{15}N$ values (Figs. 4.7f and 4.7g). In contrast, lay individuals with 4+ NSLs were likelier to have lower $\delta^{15}N$ values (≤ 10.7‰) than their peers with < 4 NSLs. Additionally, individuals without NSLs were most likely to come from the lay cemetery, regardless of their $\delta^{15}N$ values, reflecting the overall lower prevalence of NSLs in this group.

Finally, increases in age-at-death increased the odds (OR: 1.6, 95% CI = 1.1-2.4) of an individual being from the lay cemetery, suggesting that individuals in the lay cemetery were likelier to reach the oldest ages (66+ yrs), in accordance with the Kaplan-Meier results. The estimated marginal mean plot (EMM; Fig. 4.7e) shows that individuals are likelier to come from the lay cemetery at all ages, contrary to what might be expected based on age-at-death distributions (Fig. 4.3). This may suggest non-linearity of the log odds (not uncommon with bimodal data) or other confounding factors and should thus be viewed cautiously.

4.6.iii Burial Sectors

Multinomial logistic regression was used to identify which variables significantly distinguished individuals across burial sectors. Sectors 1 and 5, both high-status burial areas with overlapping chronologies and small samples, were combined ("Sector 1/5") to improve the model's accuracy. They were kept separate in the bivariate analyses.

The overall model was statistically significant ($\chi^2 = 148$, $p = < 0.001$). McFadden's R^2 was 0.25, suggesting a well-fitting model that explains 25% of the variance in the data (McFadden, 1973). Sector 1/5 was the most unique and, therefore, used as the reference group. An omnibus likelihood ratio test was used to help determine which independent variables were significant in the overall model (Table 4.10). The results indicate that age-at-death, $\delta^{13}C$ values, $\delta^{15}N$ values, estimated sex, NSL size, and interactions between age-at-death and $\delta^{13}C$ and $\delta^{15}N$ values are significant predictors for burial sector (Tables 4.10 and 4.11).

Table 4.10: Results of the omnibus likelihood ratio test. Because backward elimination was used, only statistically significant predictor variables ($\alpha = 0.10$) were retained in the final model.

Predictor	**χ^2**	**df**	**p**
Age-at-Death	8.57	4	0.073
$\delta^{13}C$	26.53	4	< .001
$\delta^{15}N$	47.13	4	< .001
Sex Estimation	43.75	8	< .001
NSL Size	11.13	4	0.025
Age-at-Death ✻ $\delta^{15}N$	13.61	4	0.009
Age-at-Death ✻ $\delta^{13}C$	12.73	4	0.013

Table 4.11: Results of multinomial multiple logistic regression analysis. The combined Sectors 1 and 5 (i.e., Sector 1/5) were set as the reference sector against which all other burial sectors were compared. Sector 1/5 (n=29) dates to the 13th-16th c. CE and is comprised of privileged burials. For sex estimation, males were set as the reference group, so all categories were compared against this. In the results, "✻" denotes an interaction term.

				Overall Model Test		
Model	**Deviance**	**AIC**	**R^2_{McF}**	**χ^2**	**df**	**p**
1	447	519	0.25	148	32	< .001

	Multinomial Logistic Regression Model Coefficients					**95% Confidence Interval**	
Burial Sector	**Predictor**	**Estimate**	**SE**	**p**	**Odds ratio**	**Lower**	**Upper**
3 (n=28) 13th-16th c. CE Mixed burials	Intercept	1.96	0.73	0.008	7.07	1.68	29.76
	Age-at-Death	-0.14	0.41	0.726	0.86	0.39	1.94
	$\delta^{13}C$	-1.02	0.45	0.024	0.36	0.15	0.87
	$\delta^{15}N$	-1.08	0.58	0.061	0.34	0.11	1.05
	Sex Estimation:						
	Ambiguous v Male	0.71	1.49	0.636	2.03	0.11	37.96
	Female v Male	-3.47	1.01	< .001	0.03	0.00	0.22
	NSL Size	-0.40	0.39	0.295	0.67	0.31	1.42
	Age-at-Death ✻ $\delta^{15}N$	-0.23	0.51	0.648	0.79	0.29	2.15
	Age-at-Death ✻ $\delta^{13}C$	0.60	0.45	0.184	1.83	0.75	4.47
4 (n=26) 15th-16th c. CE Basic burials	Intercept	2.06	0.72	0.004	7.87	1.90	32.57
	Age-at-Death	0.15	0.40	0.700	1.17	0.53	2.55
	$\delta^{13}C$	-0.14	0.45	0.749	0.86	0.36	2.10
	$\delta^{15}N$	-2.42	0.59	< .001	0.09	0.03	0.28
	Sex Estimation:						
	Ambiguous v Male	-0.30	1.63	0.854	0.74	0.03	18.06
	Female v Male	-3.25	0.97	< .001	0.039	0.00	0.26
	NSL Size	0.28	0.35	0.423	1.32	0.66	2.64
	Age-at-Death ✻ $\delta^{15}N$	-1.55	0.53	0.003	0.21	0.07	0.60
	Age-at-Death ✻ $\delta^{13}C$	1.30	0.45	0.004	3.66	1.52	8.83
6 (n=35)	Intercept	1.80	0.75	0.016	6.06	1.40	26.24
	Age-at-Death	0.50	0.40	0.219	1.64	0.74	3.63
	$\delta^{13}C$	-1.64	0.49	< .001	0.19	0.07	0.50
	$\delta^{15}N$	-1.44	0.60	0.016	0.24	0.07	0.77

12^{th}-15^{th} c. CE Mixed burials	Sex Estimation:						
	Ambiguous v Male	1.54	1.49	0.301	4.67	0.25	86.61
	Female v Male	-2.87	0.97	0.003	0.06	0.01	0.38
	NSL Size	0.15	0.37	0.682	1.16	0.56	2.43
	Age-at-Death ✻ $\delta^{15}N$	-1.08	0.52	0.038	0.34	0.12	0.94
	Age-at-Death ✻ $\delta^{13}C$	1.39	0.47	0.003	4.01	1.59	10.14
4M (n=78) 10^{th}-13^{th} c. CE Monastic burials	Intercept	3.42	0.69	< .001	30.58	7.92	118.00
	Age-at-Death	-0.26	0.38	0.499	0.77	0.37	1.62
	$\delta^{13}C$	-0.23	0.41	0.574	0.79	0.35	1.77
	$\delta^{15}N$	-2.75	0.57	< .001	0.06	0.02	0.19
	Sex Estimation:						
	Ambiguous v Male	-1.18	1.46	0.419	0.31	0.02	5.36
	Female v Male	-4.58	0.94	< .001	0.01	0.00	0.06
	NSL Size	0.53	0.32	0.092	1.70	0.92	3.16
	Age-at-Death ✻ $\delta^{15}N$	-0.95	0.50	0.057	0.39	0.15	1.03
	Age-at-Death ✻ $\delta^{13}C$	0.88	0.41	0.030	2.42	1.09	5.38

Due to differing male-to-female ratios (Table 4.2), estimated sex significantly influenced sector assignment in the model. If female, an individual was likelier to come from Sector 1/5 and 6, and Sectors 3, 4, and 4M (monastic) if male.

Because multinomial logistic regression compares each sector against the reference, the EMM plots provide a more interpretable representation of the results (Fig. 4.8). Figure 4.8b indicates that individuals from Sectors 1/5 are most likely to have the highest $\delta^{15}N$ values (≥11.4‰) when the other predictor variables are held constant. Individuals from the monastic cemetery (4M) are most likely to have the lowest $\delta^{15}N$ values (≤10‰), and Sectors 3, 4, and 6 fell in between. For $\delta^{13}C$ values, Figure 4.8a indicates individuals from Sectors 1/5, 4, and 4M were likelier to have higher $\delta^{13}C$ values (≥ -18.3‰), and individuals from Sector 6 were most likely to have the lowest $\delta^{13}C$ values (≤ -19.1‰).

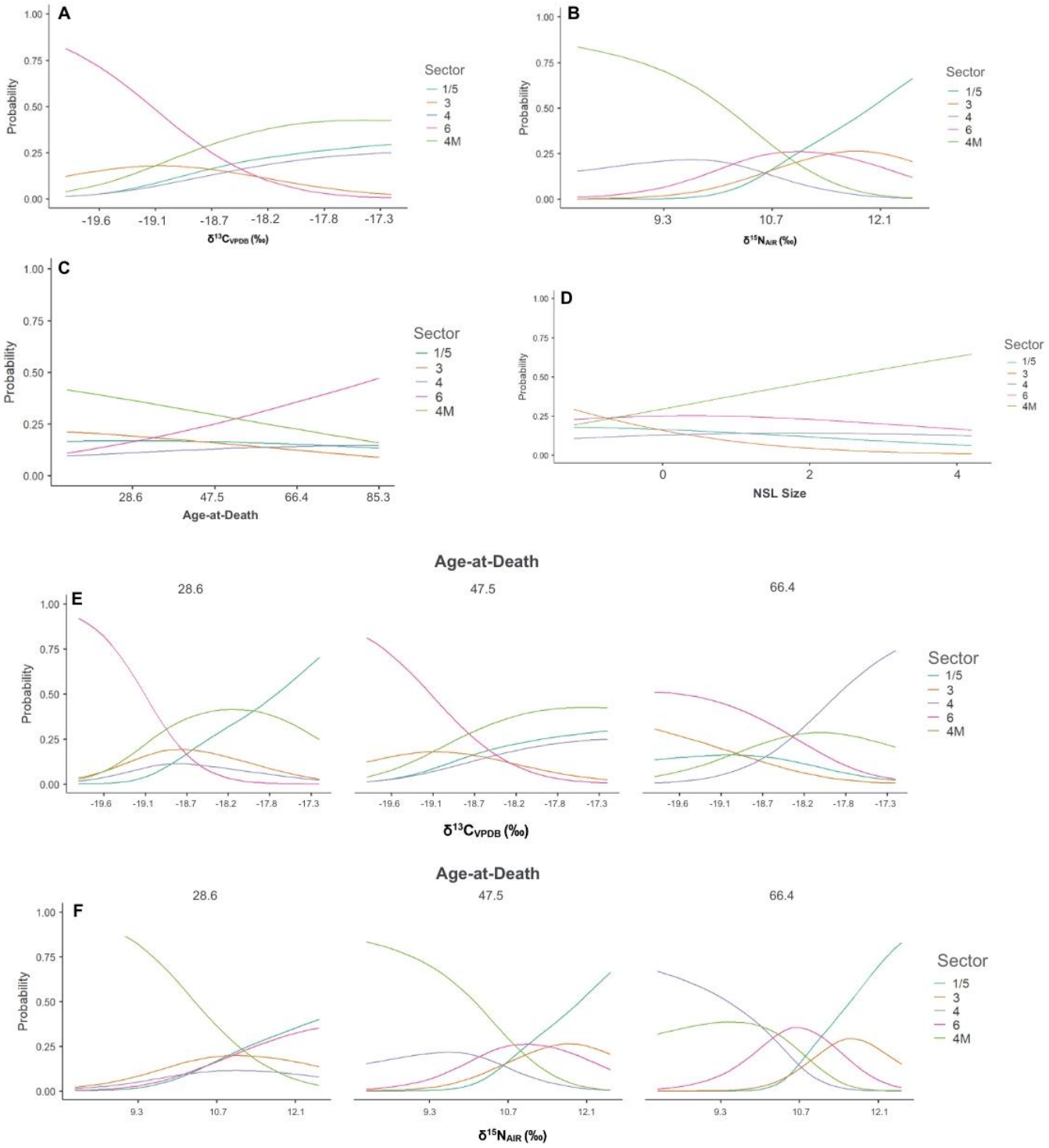

Figure 4.8: Estimated marginal mean plots (EMM) for the multinomial logistic regression. The EMMS visualizes the relationship between the probability of coming from a burial sector based on the independent variable value including: A) $\delta^{13}C$ values, B) $\delta^{15}N$ values, C) age-at-death, D) NSL size represented by the number of bone regions a NSL extends across, E) $\delta^{13}C$ values based on age-at-death [interaction term], F) $\delta^{15}N$ values based on age-at-death [interaction term].

For NSL size, Figure 4.8d shows that individuals in Sector 3 were likelier to have either no or smaller NSLs, while the monastic cemetery (4M) was still most likely to have larger NSLs. Table 4.9 presents the results of the supplemental chi-squared and ANOVA analyses on the lay burial sectors. There was no significant difference in NSL prevalence across the lay burial sectors ($p = 0.127$), though Sectors 3 and 5 had lower prevalence rates. There were also no statistically significant differences for NSL bone type ($p = 0.87$), NSL number ($p = 0.09$), or the number of bones with NSLs ($p = 0.18$).

The omnibus likelihood test indicates that age-at-death was significant in the overall model, though none of the coefficient estimates were statistically significant. This implies that age-at-death helps explain the outcome (i.e., burial sector), but the relationship may be complex. The EMM (Fig. 4.8c) suggests that Sectors 4 and 6 differed from the others, and individuals aged 66+ years were likelier to be from these sectors, particularly Sector 6, which aligns with the Kaplan-Meier results (Fig. S4.2). Significant interaction terms between age-at-death and $\delta^{13}C$ and $\delta^{15}N$ values were also evident. This indicates differing relationships between age-at-death and $\delta^{13}C$ and $\delta^{15}N$ values across the burial sectors (Fig. 4.8e and 4.8f). Individuals aged 47+ in Sector 4 were likelier to have higher $\delta^{13}C$ values ($\geq$ -18.2‰) than younger individuals. In contrast, individuals aged 66+ in Sectors 1/5 were likelier to have lower $\delta^{13}C$ values. For $\delta^{15}N$ values, the data suggest that individuals aged 47+ in Sectors 4 and 6 were likelier to have lower $\delta^{15}N$ values than younger ones.

4.7 DISCUSSION

4.7.i Monastic versus Lay

Marine environments have longer and more complex food chains, and carbon originates from dissolved carbonate ($\delta^{13}C$ value - 0‰) with higher $\delta^{13}C$ values than terrestrial carbon sources (atmospheric $C0_2$) (Katzenberg & Waters-Rist, 2018). As a result, individuals who consume marine resources have higher $\delta^{13}C$ and $\delta^{15}N$ values. The ~5‰ $\delta^{15}N$ difference between humans and terrestrial fauna for Osor's sample (Fig. 4.4) suggests a mixed, primarily terrestrial-protein-based diet with some marine input, similar to earlier regional populations (e.g., Čaušević-Bully et al., 2023; Zagorc et al., 2024). Dietary variation across Osor appeared to be a matter of more or less marine resource consumption.

Medieval sources from the eastern Adriatic coast identify sardine, mackerel, bluefin tuna, pickerel, oysters, mullet, sea bass, common sea bream, and squid as common species found in this region and period (Fabijanec, 2016, 2021). Sardines, mackerel, and bluefin tuna were among the most common, with tuna being an expensive, prized resource associated with privileged diets (Fabijanec, 2021; Squatriti et al., 2000). The differences in $\delta^{15}N$ values for lower trophic-level fish species, such as sardines and anchovies, were closest to approaching the average 3‰ $\delta^{15}N$ and 1‰ $\delta^{13}C$ trophic level shift between consumers and food. In aggregate, lower trophic-level marine foods may have been more prevalent in Osor's diet than higher trophic-level marine resources, such as tuna. Higher trophic marine species (e.g., tuna, mullet) had $\delta^{15}N$ and $\delta^{13}C$

values exceeding humans, suggesting that if individuals at Osor were consuming these resources, they were doing so infrequently.

The $\delta^{13}C$ values suggest that C3 plants ($\delta^{13}C$ -38‰ to -22‰) generally formed the basis of both the human and terrestrial fauna's diets. The more positive $\delta^{13}C$ values seen across faunal species could suggest some supplementation with C4 ($\delta^{13}C$: -16‰ to -9‰) grains (Bogaard et al., 2013; Čaušević-Bully et al., 2023; Madgwick et al., 2012). Some individuals in the monastic and lay samples have higher $\delta^{13}C$ values and lower $\delta^{15}N$ values, attesting to some consumption of C4 plants. Cereal grains such as soft wheat, durum wheat, and barley (C3 plants) were important staples in this region, and millet (C4 plant) is known to have been consumed by late Antique and early medieval Croatian populations (Čaušević-Bully et al., 2023; Lightfoot et al., 2012; Zagorc et al., 2024).

The results confirmed significant differences between the monastic and lay cemeteries, but often not in the hypothesized patterns. Individuals from the monastic cemetery did not have a notably "richer" diet than those in the lay cemetery. Rather, the monastic individuals were significantly more likely to have lower $\delta^{15}N$ and higher $\delta^{13}C$ values. For $\delta^{13}C$, the analysis by burial sector indicates that individuals from Sector 6 are largely driving this trend (Fig. 4.8a).

Since bone collagen reflects a multi-year average of dietary protein, these patterns may result from various factors. Excavations of St. Peter's monastic complex found a large deposit of mollusk shells in a kitchen area (Marić et al., 2014; Rizner, 2017). Thus, the monastic diet may have included more lower-trophic marine resources, which modern isotope data show have similar $\delta^{15}N$ and slightly higher $\delta^{13}C$ values than the medieval terrestrial animals (Zorica et al., 2021). It should be noted that anthropogenic activity has resulted in higher $\delta^{15}N$ and lower $\delta^{13}C$ values in modern aquatic species (Häberle et al., 2016). Historical sources suggest shellfish, including oysters, mussels, and scallops, were a prized food commodity in monasteries due to their seasonality (Thomas & Hero, 2000). The monastic group's diet could also have included a greater degree of millet, resulting in elevated $\delta^{13}C$ values paired with lower $\delta^{15}N$ values.

The monastic diet differed significantly from that of Osor's elites in Sectors 1 and 5. The differences in $\delta^{15}N$ combined with the less pronounced differences in $\delta^{13}C$ (Fig. 4.8a and 4.8b) suggest that Osor's elite had a more protein-rich diet, potentially including more or different marine resources. The data suggest Osor's elite did not regularly consume costly, high-trophic marine foods like tuna, though they likely had greater access to such resources through wealth, fishing rights, or control over fishing grounds and their yields (Fabijanec, 2016, 2021). Contrary to other medieval monastic communities (e.g., Cirelli, 2013; Harvey, 1997; Janeš & Bedić, 2020; Mays, 1997; Novak, 2013; Živaljević et al., 2019), the results indicate that the average monastic diet was more similar to Osor's non-privileged secular population in Sectors 4 and 6 than the privileged buried in Sectors 1 and 5 (Fig. 4.6).

St. Peter's was a Camaldolese order, which put more emphasis on austere simplicity, including fasting, silence, and contemplation, than other Benedictine orders (Čaušević-Bully et al., 2014; Lawrence & Burton, 2023). However, average stable isotope values for St. Peter's Monastery also resemble later (1600-1700s A.D.) Benedictine nuns from St. Theodore's in Pula,

Croatia (average = $\delta^{13}C$: -18.6‰, $\delta^{15}N$: 10.3‰; Carić & Novak, 2024). Therefore, these results may suggest either more austere dietary practices at St. Peter's monastery or reflect regional dietary practices for eastern Adriatic religious communities.

There was a significant range of stable isotope values within the monastic cemetery (range = 2.6‰ $\delta^{13}C$, 3.0‰ $\delta^{15}N$), and some monastic individuals did have isotope values resembling those of Osor's elite. In Sector 1, burial goods suggest one individual was a priest, linking more marine-rich diets to Osor's later religious community (1200–1500 A.D.). Monastic hierarchies meant that higher-status individuals, such as abbots, priors, and senior monks, often enjoyed more privileged diets (Gregoricka & Sheridan, 2013; Harvey, 1997). It was also not uncommon for bishops or nobles to retire to religious communities at the end of their life and monastic cemeteries were privileged burial location for high-status lay persons (Constable, 2017). This may explain dietary variation within the monastic group.

The binary logistic regression results suggest that the monastic group was less likely to reach the oldest ages-at-death (60+ yrs). The Kaplan-Meier survival analysis (Fig. S4.1) corroborates this, although the differences in survivorship were not statistically significant. The low number of 10–25-year-olds in the monastic group likely reflects the absence of females—who comprise much of that age group among laypeople—and entry policies that set minimum admission ages around 15–20 years (Constable, 2017). Individuals in the monastic cemetery had a significantly greater prevalence of NSLs. Due to the osteological paradox, this could indicate patterns of resilience or frailty. Here, NSL presence was associated with greater median survival times (Fig. S4.3), indicating that NSL presence was generally a marker of resilience across this sample. However, this did not translate to lower mortality risk for the monastic group (Fig. S4.1).

NSL characteristics in the monastic group may suggest differing trends in the types of nonspecific stress these groups experienced. NSL size can be affected by the aggressiveness, intensity, and duration of the conditions that result in their formation (Ragsdale et al., 1981, 2018). Solid, continuous, and thicker periosteal new bone formations can connote chronic conditions with a slow rate of progression (Ragsdale, 1993; Wenaden et al., 2005). Lamellar and mixed NSLs can further indicate either the survival of a stressor or that a stressor persisted long enough for remodelling of the initial woven periosteal new bone to occur. Most NSLs across the sample were lamellar, and NSL bone composition did not significantly differ between the monastic and lay cemeteries. However, the monastic individuals tended to have larger NSLs and a greater prevalence.

It has been hypothesized that monastic lifestyles resulted in greater risks for metabolic disorders. DISH (Diffuse Idiopathic Skeletal Hyperostosis) is one such metabolic disorder that has garnered particular attention. Some studies have shown higher prevalences of DISH in monastic communities (Patrick, 2014; Verlaan et al., 2007; Waldron, 1985) and established a connection with higher $\delta^{15}N$ values in some cases (Müldner & Richards, 2007) but not in others (Quintelier et al., 2014; Spencer, 2008). Mays (2006) cautions that some of these patterns may result from sample bias, as monastic cemeteries represent a specific at-risk group (i.e., middle-aged males). Metabolic diseases such as DISH and gout are associated with co-morbidities, such as circulatory disorders, that can create the conditions for larger NSLs to form, particularly on

the lower limbs (Adler, 2000; Harlianto et al., 2022; Ragsdale & Lehmer, 2011; Resnick, 1988; Singh & Gaffo, 2020).

This study did not systematically examine metabolic diseases; thus, while conditions like DISH can be noted anecdotally, further research is needed to identify meaningful patterns. The results indicate that monastic individuals with more and larger NSLs were likelier to have higher $\delta^{15}N$ values (Fig. 4.7e and 4.7g), indicating a possible association with diet, though they do not suggest that monks had a "richer" diet in the aggregate. While the rules of St. Benedict prescribed manual labor, from the eleventh century onwards, manual work was often eliminated or reduced in favor of more intellectual activities (Lawrence & Burton 2023). Those facets associated with monastic life, including a more protected and sedentary lifestyle alongside a regular, if not "richer" diet, may have translated to greater susceptibility to certain health conditions that resulted in larger NSLs and contributed to observed mortality outcomes. This contrasts with the lay sample, where more NSLs were linked to lower $\delta^{15}N$ values, underlining that differing biocultural factors may have influenced nonspecific stress in these two groups.

4.7.ii Sectors

The results revealed interesting differences between the lay burial sectors. Like contemporary populations (e.g., Novak et al., 2017), elite individuals from Sectors 1 and 5 had diets with more protein and/or marine resources. The overlapping chronologies of the lay burial sectors (Table 4.1) suggest that dietary changes with time aren't likely to be driving these differences, though they may have still contributed. However, this did not confer the health advantages seen in other populations. This was particularly true for Sectors 1, 3, and 5, which had the lowest mean ages-at-death (Table 4.4) and survival times (Fig. S4.2). Although NSL prevalence did not differ significantly across lay sectors, Sectors 3 and 5 showed a pattern of lower survival times and lower NSL rates—traits associated with increased frailty (Fig. S4.3). Sector 1 did not show similarly low NSL prevalence, possibly reflecting different relationships between NSLs and frailty, or limitations due to small sample size.

The thirteenth to fifteenth centuries in Osor witnessed outbreaks of plague, malaria, and violence (Protić, 2015). Plague struck Osor in 1361, and documentation of successive outbreaks on the neighboring island of Rab in the 1300-1400s A.D. raises the possibility of further outbreaks (Mlacović, 2012). The impact of significant mortality events like plague can be lost in the aggregate of long-term data (DeWitte & Stojanowski, 2015; Wood et al., 1992). Sector 5 dates more exclusively within this period (1200-1400s A.D) and Sector 3 lay burials also predominately date to the 1200-1400s A.D., so these data may reflect some of the impacts of these significant events more so than the other burial sectors whose use extended across preceding and succeeding centuries (Marić et al., 2014).

Alternatively, these patterns could reflect heterogeneous frailty stemming from lifestyle factors. In this sample, higher $\delta^{15}N$ values are correlated with younger ages-at-death. Higher $\delta^{15}N$ values were associated with higher $\delta^{13}C$ values, suggesting a stronger link to dietary variation rather than stress (Fuller et al., 2005). The more protein- and marine-resource-rich diets

in this sample tend to be associated with higher status and could be a lifestyle marker that resulted in greater health risks to those individuals. Indeed, Sector 3 likely also included Osor's local aristocracy (Čaušević-Bully et al., 2011).

Additionally, Sector 6 (1000-1400s A.D.) demonstrated distinctive patterns. These individuals had higher mean ages-at-death, with those aged 66+ years most likely to be from this sector. The multinomial logistic regression results also suggest that individuals from Sector 6 were most likely to have lower $\delta^{13}C$ values, indicating a more terrestrial-protein-based diet. Individuals in privileged and basic burials both had lower $\delta^{13}C$ and $\delta^{15}N$ values in contrast to what might be expected based on data from Sectors 1, 3, and 5. This variation may potentially stem from increased migration to coastal and island regions during the 1200–1400s A.D., driven by conflict on the mainland (Ivetić, 2022; Mlacović, 2012). Monasteries could also draw people in as they were centers of economic activity and religious life (Ivetić, 2022).

The results also revealed interesting relationships between diet and age across the burial sectors. For instance, the types of proteins consumed might have varied or diminished with increased age in Sectors 4 and 6. However, the limitations of archaeological data, including chronologies spanning multiple centuries and sample size, make it challenging to determine whether this data reflects different dietary patterns over individuals' life courses, results from heterogeneity within the samples, or is merely the outcome of sample size. A more focused analysis incorporating more samples could provide greater clarity on this.

4.8 CONCLUSION

This investigation into intrapopulation variation in the medieval Osor St. Peter's cemetery reveals significant diversity and interrelationships between diet, nonspecific stress indicators, and mortality risks across its monastic and lay communities. The findings disproved many of our original hypotheses based upon previous research. The results indicate that the dietary patterns of the monastic community at St. Peter's, a significant center of religious reform at the time, were, in aggregate, significantly different from those of Osor's lay community, particularly Osor's elite. While monastic individuals experienced a greater prevalence of NSLs, which was generally associated with resilience in this sample, this did not ultimately translate into a lower mortality risk, as seen in other medieval monastic populations. These data may indicate potential vulnerabilities associated with the monastic lifestyle, possibly linked to chronic health conditions.

Additionally, although the elite lay individuals had more protein-rich diets, as hypothesized, that incorporated more marine resources, they did not enjoy corresponding health benefits. This was evidenced by patterns of nonspecific stress and mortality risk indicative of greater rates of frailty rather than resilience. Additionally, Sector 6 demonstrated differing, more terrestrial protein-based dietary patterns and possible alternative associations between diet and status that set them apart from other burial sectors. The results of this study underscore the benefits of a multivariable approach. Further isotopic studies incorporating Bayesian modeling

could help elucidate the proportion of marine versus terrestrial protein in this sample's diet. Future studies examining migration and more detailed paleopathological analysis of metabolic disease can also build upon the results presented here. Lastly, further examination of the burials' chronology could help shed light on possible temporal trends and differences in mortality risk.

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SUPPLEMENTAL FILE 1: SUPPLEMENTAL RESULTS

Supplementary Table S4.1: Missing Completely at Random (MCAR) results

EM Means[a]

AgeatDeathSimplified	SI_Carbon_Rib	SexEstimationMFAU	SI_Nitrogen_Rib
47.4787	-18.7215	.37	10.6909

a. Little's MCAR test: Chi-Square = 10.378, DF = 10, Sig. = .408

Table S4.2: Spearman's correlation results testing for a correlation between nonspecific lesion presence and erosion/abrasion score. The results indicate no correlation between erosion/abrasion score and nonspecific lesion presence suggesting that taphonomic damage did not skew the paleopathological data

		Erosion/ Abrasion
NSL Presence	Spearman's rho	-0.052
	df	190
	p-value	0.473

Supplementary Table S4.3: Results for Pearson's correlation between Age-at-Death and $\delta^{13}C$ and $\delta^{15}N$ values

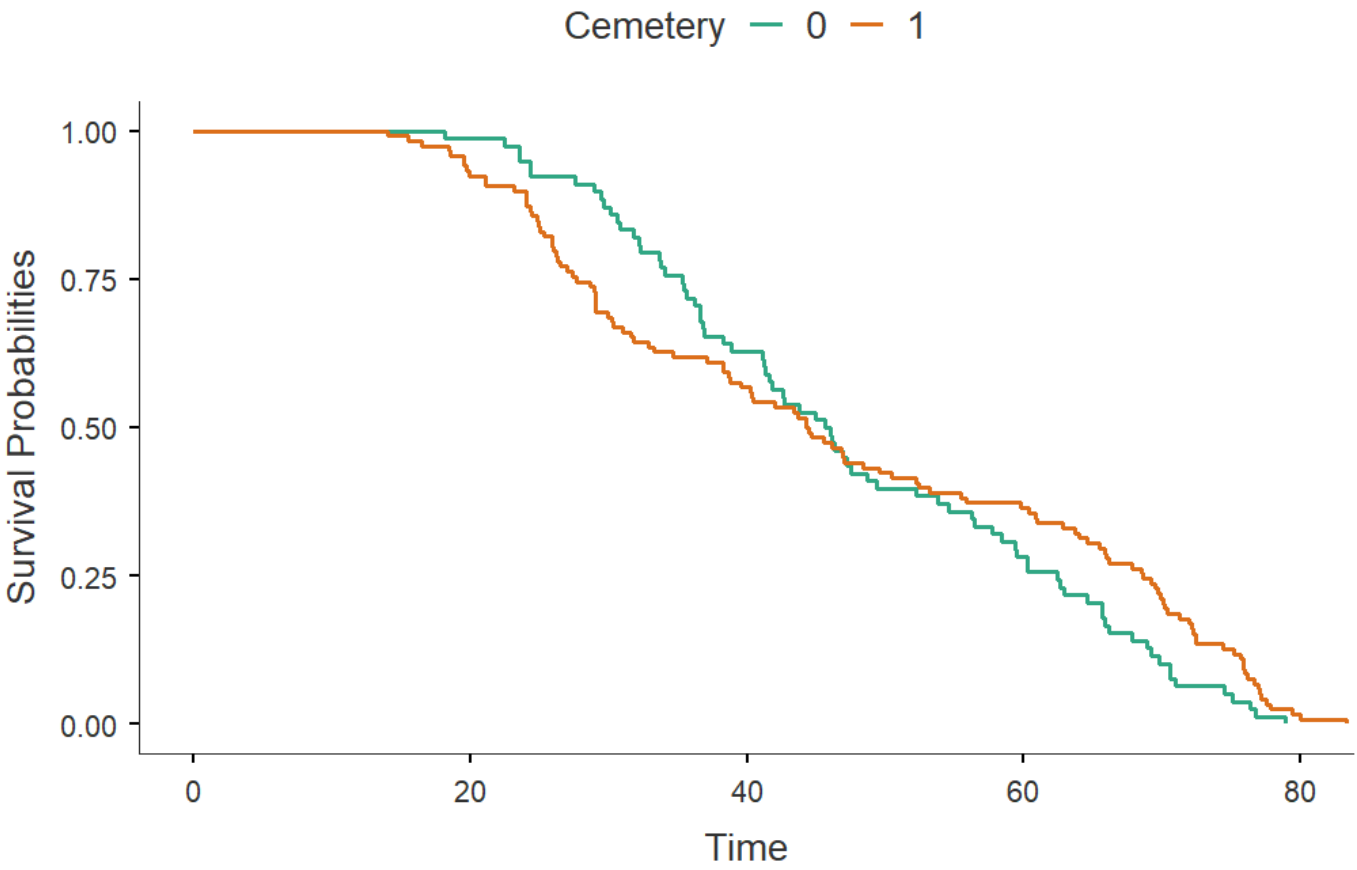
Pearson's R Correlation		
	Age-at-Death	
Nitrogen	Pearson's r	-0.231
	df	194
	p-value	0.001
Carbon	Pearson's r	-0.060
	df	194
	p-value	0.402

Supplementary Table S4.4: Results of Welch's t-test between NSL absence/presence and δ13C and δ15N values

Variable	T-Test	Statistic	df	p	Mean difference
Carbon	Welch's t	-0.152	153	0.879	-0.01
Nitrogen	Welch's t	1.055	132	0.293	0.11

Supplementary Table S4.5: Results of Kaplan-Meier survival analysis grouped by cemetery (i.e., monastic vs. lay). The results indicate that there were no overall significant differences in the survival times between the monastic and lay individuals. The Tarone-Ware test of significance was selected as it balances out early and late life-events.

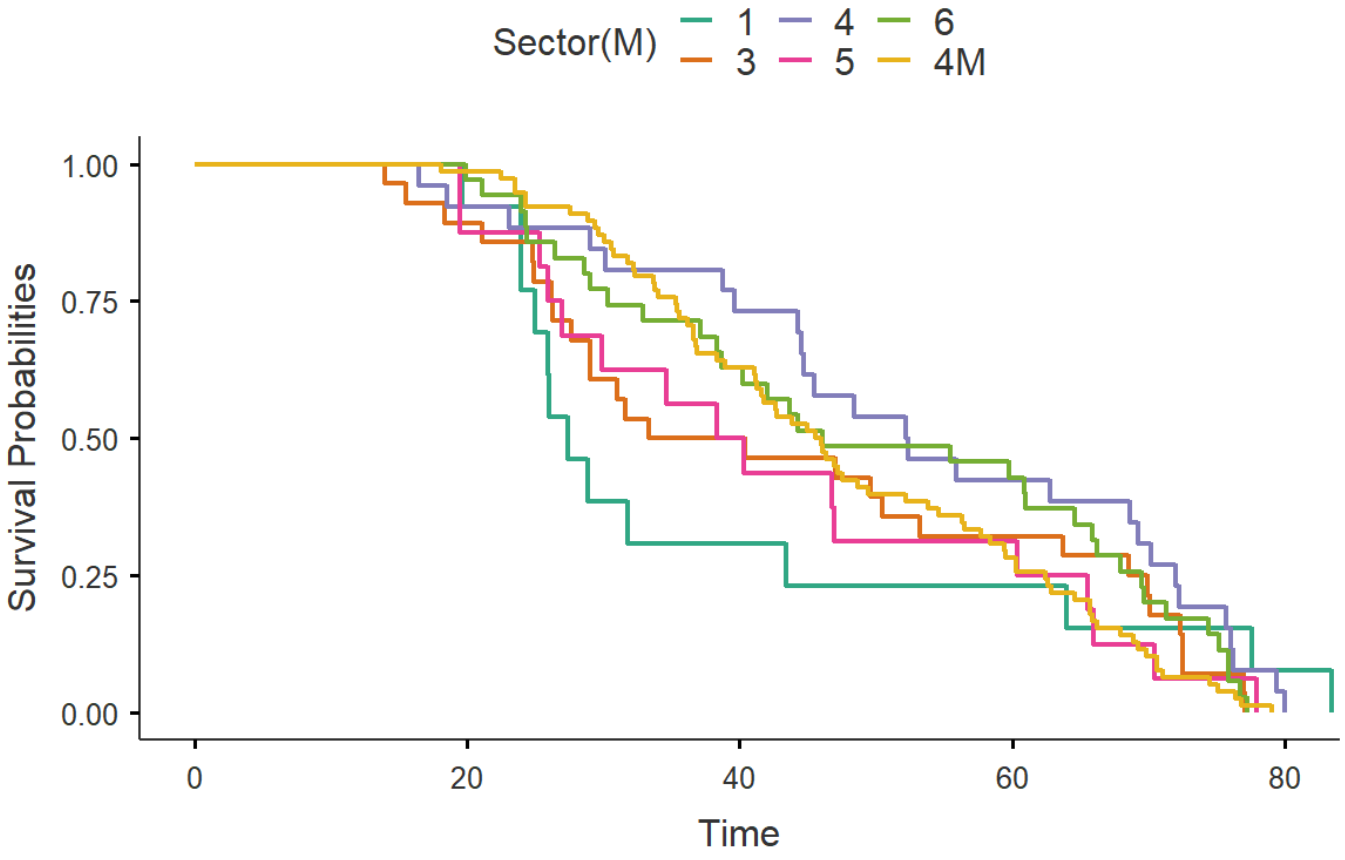
		95% Confidence Interval		
Cemetery	**Median Survival Time**	**Lower**	**Upper**	**p-value (Tarone-Ware)**
Monastic	45.8	41.3	53.8	0.698
Lay	44.4	38.8	52.4	



Supplementary Figure S4.1: Results of Kaplan-Meier survival analysis grouped by cemetery. The Lay cemetery is coded as "1" and the Monastic cemetery as "0". The results suggest that lay individuals had greater survivorship at older ages (i.e., 60+ yrs) compared to the monastic group, although this trend was not statistically significant. This aligns with the results of the binary logistic regression analysis.

Supplementary Table S4.6: Results of analysis of difference for Kaplan-Meier survival analysis grouped by burial sector. These results indicate that burial sectors 1, 3, and 5 had lower median survival times than individuals in other burial sectors. The Tarone-Ware test of significance was selected as it balances out early and late life-events.

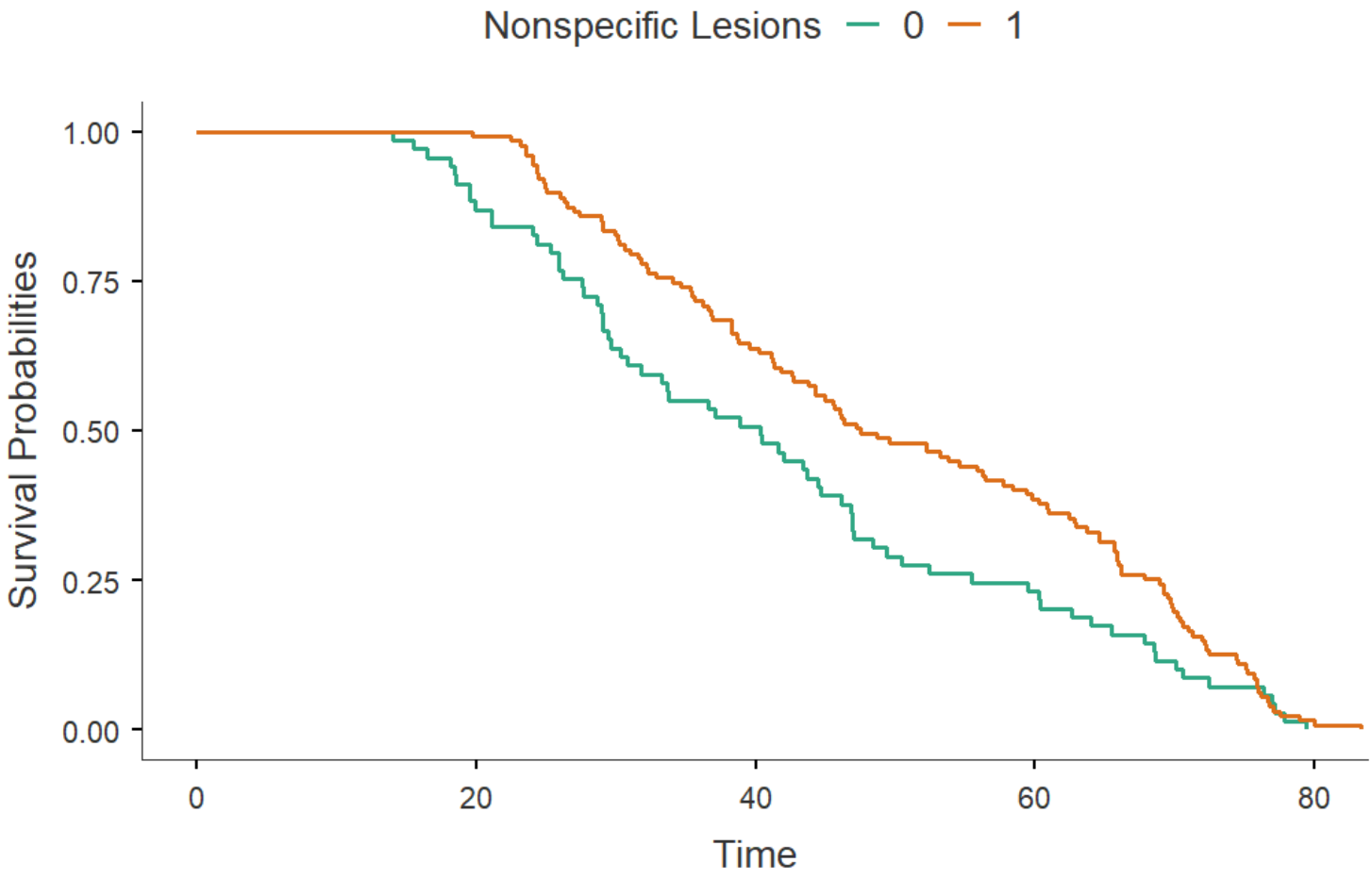
		95% Confidence Interval		
Burial Sector	**Median Survival Time**	**Lower**	**Upper**	**p-value (Tarone-Ware)**
1	27.4	25.0	NaN	< 0.001
3	36.8	29.0	68.5	
4	52.3	44.5	72.0	
5	39.3	27.0	66.0	
6	46.1	38.7	66.2	
4M	45.8	41.3	53.8	



Supplemental Figure S4.2: Results of the Kaplan-Meier Survival Analysis. The results suggest that individuals in Sectors 1, 3, and 5 experienced lower survivorship than their peers in Sectors 4 (lay), 6 (lay), and 4M (monastic).

Supplemental Table S4.7: Results of Kaplan-Meier survival analysis between individuals without (i.e., "0") and with (i.e., "1") nonspecific lesions. The results indicate there were significant differences in mean survival times and survivorship.

		95% Confidence Interval		
Nonspecific Lesions	**Median Survival Time**	**Lower**	**Upper**	**p-value (Tarone-Ware)**
Absent (0)	40.3	31.8	46.8	0.002
Present (1)	47.5	43.8	58.4	



Supplemental Figure S4.3: Results of the Kaplan-Meier Survival Analysis. The results indicate that individuals with no nonspecific lesions (i.e., "0") consistently lower survivorship than those with nonspecific lesions (i.e., "1").

SUPPLEMENTAL FILE 2: STABLE ISOTOPE QUALITY CONTROL AND DATA

Stable Isotope Quality Control Indicators

Analytical precision is based on an internal standard (C- 55) (glutamic acid) and is better than ± 0.2‰ for both $\delta^{15}N$ and $\delta^{13}C$. Analytical precision is based on the internal check standard C- 55 $\delta^{15}N$ of -3.9 and $\delta^{13}C$ of − 28.5. Internal laboratory calibration standards are as follows: ($\delta^{15}N$, $\delta^{13}C$ in ‰): C-51 Nicotinamide ($\delta^{15}N$ 0.07‰, $\delta^{13}C$ − 22.95‰), C- 52 mix of ammonium sulphate + sucrose ($\delta^{15}N$ 16.58‰, $\delta^{13}C$ −11.94‰), C-54 caffeine ($\delta^{15}N$ −16.61‰, $\delta^{13}C$ −34.46‰). The check standards for each session (n=6) are reported in Table S4.8.

All $\delta^{15}N$ is reported as ‰ vs. AIR and normalized to internal standards calibrated to International standards IAEA-N1(+0.4‰), IAEA-N2(+20.3‰), USGS-40(-4.52‰) and USGS-41(47.57‰). The calibration standards are as good as or better than the check standard. In each case the calibration is R2 = 0.999x or better. All $\delta^{13}C$ is reported as ‰ vs. V-PDB and normalized to internal standards calibrated to International standards IAEA-CH-6(-10.4‰), NBS-22(-29.91‰), USGS-40(-26.24‰) and USGS-41(37.76‰).

Supplementary Table S4.8: Checks and standards for each stable isotope session

Session ID	Check Standard	N	$\delta^{13}C$ (‰, VPDB) Mean and SD	$\delta^{15}N$ (‰, AIR) Mean and SD
1	C-55 (glutamic acid)	3	-28.4 ± 0.1	-4.0 ± 0.1
2	C-55 (glutamic acid)	4	-28.5 ± 0.1	-4.0 ± 0.1
3	C-55 (glutamic acid)	3	-28.6 ± 0.1	- 3.9 ± 0.1
4	C-55 (glutamic acid)	3	-28.5 ± 0.1	-4.0 ± 0.1
5	C-55 (glutamic acid)	3	-28.5 ± 0.1	-3.9 ± 0.1
6	C-55 (glutamic acid)	3	-28.6 ± 0.1	-3.9 ± 0.1

Stable Isotope Methods for Institute for Anthropological Research, Zagreb Samples

Samples from rib bones were demineralized in 0.5 M aq. HCl at 4°C until demineralized. Samples were rinsed with de-ionized water and then gelatinized in acidic solution (pH 3) at 70°C for 48 hours. The liquid solution containing the gelatinized protein was frozen for 24 hours and then freeze-dried for 48 hours to obtain the final collagen product. Carbon and nitrogen isotope analysis was undertaken by Elemental Analysis - Isotope Ratio Mass Spectrometry (EA-IRMS).

Samples and references were weighed into tin capsules, sealed, and loaded into an auto-sampler on a Europa Scientific elemental analyser and accelerated. The reference material used for $\delta^{13}C$ and $\delta^{15}N$ analysis of the collagen samples was IA-R068 (soy protein, δ^{13}CV-PDB = -25.22 ‰, δ^{15}NAIR = 0.99 ‰). IA-R068, IA-R038 (L-alanine, δ^{13}CV-PDB = -24.99 ‰, δ^{15}NAIR = -0.65 ‰), IA-R069 (tuna protein, δ^{13}CV-PDB = -18.88 ‰, δ^{15}NAIR = 11.60 ‰) and a mixture of IAEA-C7 (oxalic acid, δ^{13}CV-PDB = -14.48 ‰) and IA-R046 (ammonium sulphate, δ^{15}NAIR = 22.04 ‰) were run as quality control check samples during analysis of the collagen samples. IA-R068, IA-R038 and IA-R069 are calibrated against and traceable to IAEA-CH-6 (sucrose, δ^{13}CV-PDB = -10.449 ‰) and IAEA-N-1 (ammonium sulphate, δ^{15}NAIR = 0.40 ‰). IA-R046 is calibrated against and traceable to IAEA-N-1. IAEA-C7, IAEA-CH-6 and IAEA-N-1 are inter-laboratory comparison standards distributed by the International Atomic Energy Agency, Vienna.

Comparison Between Current Study and Institute for Anthropological Research Stable Isotope Values

Stable isotope analysis had previously been completed for n=40 rib samples from the Osor St. Peter osteological sample. Of these previously run samples, n=12 was re-run following the procedures outlined in this study to ensure that differing methods and lab protocols did not produce significantly different results. A paired t-test was used to test for significantly different $\delta^{15}N$ and $\delta^{13}C$ results between the two labs. The results indicate that $\delta^{13}C$ values were not statistically significantly different. The $\delta^{15}N$ values were significantly different, but the mean difference was 0.2‰ and thus within the realm of standard error. This indicates that the stable isotope results did not meaningfully differ from one another.

Supplementary Table S4.9: $\delta^{13}C$ and $\delta^{15}N$ values descriptive statistics for Propst et al. (2025) and the Institute's stable isotope samples

	N	Mean	Median	SD	SE
$\delta^{13}C$ (Propst)	12	-18.6	-18.5	0.355	0.1025
$\delta^{13}C$ (Inst)	12	-18.5	-18.5	0.326	0.0942
$\delta^{15}N$ (Propst)	12	11.0	11.2	0.705	0.2035
$\delta^{15}N$ (Inst)	12	10.9	11.0	0.626	0.1807

Supplementary Table S4.10: Results of t-test comparing stable isotopes value from different labs (Propst = current study; Inst = Institute for Anthropological Research)

			Statistic	df	p	Mean difference
$\delta^{13}C$ (Propst)	$\delta^{13}C$ (Inst)	Student's t	-0.407	11.0	0.692	-0.0241
$\delta^{15}N$ (Propst)	$\delta^{15}N$ (Inst)	Student's t	3.365	11.0	0.006	0.1767

Stable Isotope Data

Osor St. Peter Human Values

Supplementary Table S4.11: Stable Isotope results for Osor St. Peter's Human Samples. QCD indicates Quality Control Datum.

Sample ID	Weight (mg)	$\delta^{13}C$ (‰) vpdb	%wt C	$\delta^{15}N$ (‰) air	%wt N	Atomic C:N	Yield %
2	0.7	-18.52	51.0	10.82	18.1	3.29	9.0
2 QCD	0.7	-18.61	48.2	10.92	17.1	3.29	9.0
5	0.7	-18.20	48.8	11.56	17.2	3.31	6.0
7	0.7	-18.51	39.0	11.04	13.9	3.27	7.0
8	0.7	-18.43	47.4	11.65	16.7	3.31	4.0
9	0.7	-19.55	41.5	10.07	14.8	3.26	5.0
11	0.7	-19.03	27.6	10.9	9.8	3.28	4.0
12	0.7	-18.26	44.1	11.73	15.6	3.30	9.0
12 QCD	0.7	-18.24	42.7	11.76	15.1	3.3	9.0
17	0.7	-18.36	36.3	10.97	12.9	3.27	5.0
18	0.7	-18.39	50.7	11.22	18.3	3.23	5.0
20	0.7	-19.74	30.1	9.87	10.5	3.36	4.0
24	0.7	-19.15	34.8	11.06	12.4	3.27	6.0
33	0.7	-19.17	34.5	10.91	12.5	3.23	4.0
34	0.7	-18.71	44.8	10.74	15.9	3.29	4.0
36	0.7	-18.61	40.6	11.47	14.4	3.29	5.0
41	0.7	-18.52	39.7	10.56	14.2	3.25	4.0
50	0.7	-18.42	45.3	11.20	16.1	3.28	4.0
53	0.7	-18.55	51.7	10.73	18.4	3.28	8.0
53 QCD	0.7	-18.56	44.2	10.67	15.7	3.28	8.0
59	0.7	-18.69	44.1	10.73	15.8	3.25	5.0

61	0.7	-19.08	52.6	10.43	18.9	3.25	4.0
63	0.7	-18.57	49.6	11.34	17.4	3.32	4.0
64	0.7	-18.44	49.0	11.56	17.3	3.30	4.0
65	0.7	-18.32	37.7	11.39	13.6	3.24	4.0
66	0.7	-19.13	41.6	10.27	14.9	3.25	4.0
67	0.7	-18.84	42.9	10.29	15.2	3.29	7.0
69	0.7	-18.54	44.7	10.80	15.9	3.28	8.0
69 QCD	0.7	-18.49	42.2	10.66	15.1	3.26	8.0
70	0.7	-18.61	53.6	11.18	18.8	3.32	4.0
71	0.7	-18.99	49.1	10.59	17.3	3.31	4.0
77	0.7	-18.60	42.6	11.39	15.1	3.29	4.0
78	0.7	-18.76	46.8	11.67	16.6	3.29	7.0
79	0.7	-18.30	43.8	12.21	15.5	3.30	4.0
81	0.7	-18.85	36.0	10.26	13.0	3.22	6.0
84	0.7	-18.74	50.3	11.33	17.6	3.33	5.0
85	0.7	-19.42	36.3	9.95	13.1	3.24	5.0
90	0.7	-18.03	49.4	11.61	17.4	3.31	4.0
94	0.7	-18.62	44.6	10.85	15.8	3.29	3.0
95	0.7	-18.59	43.0	10.56	15.3	3.28	4.0
97	0.7	-19.23	46.1	10.06	16.3	3.30	5.0
98	0.7	-18.33	54.4	11.47	19.6	3.24	4.0
101	0.7	-18.93	46.1	11.09	16.4	3.28	6.0
101 QCD	0.7	-19.03	39.5	10.84	14.0	3.28	6.0
102	0.7	-19.21	40.3	11.17	14.4	3.27	5.0
105	0.7	-19.10	52.0	10.23	18.4	3.30	4.0
111	0.7	-18.17	46.9	10.33	16.5	3.31	8.0
111 QCD	0.7	-18.22	47.7	10.49	16.7	3.33	8.0
112	0.7	-18.75	49.7	10.80	17.7	3.27	4.0

114	0.7	-18.07	51.7	11.82	18.4	3.28	6.0
120	0.7	-18.15	52.5	11.16	18.8	3.26	13.0
120 QCD	0.7	-18.11	49.9	11.19	17.9	3.25	13.0
128	0.7	-17.33	38.5	11.76	13.8	3.25	5.0
129	0.7	-18.62	43.8	11.01	15.6	3.27	10.0
129 QCD	0.7	-18.64	47.3	11.05	16.7	3.3	10.0
130	0.7	-17.86	47.9	11.44	17.2	3.25	10.0
130 QCD	0.7	-17.84	40.2	11.17	14.4	3.25	10.0
131	0.7	-18.97	40.8	9.58	14.5	3.28	3.0
143	0.7	-19.46	40.6	9.05	14.6	3.25	4.0
144	0.7	-18.76	41.5	10.53	14.9	3.26	4.0
147	0.7	-18.73	55.7	10.19	19.9	3.26	6.0
149	0.7	-19.16	40.6	10.19	14.5	3.28	5.0
153	0.7	-18.63	54.3	10.28	18.9	3.35	4.0
156	0.7	-19.03	48.4	10.19	17.1	3.30	6.0
157	0.7	-19.51	25.7	11.08	9.1	3.29	7.0
164	0.7	-19.21	35.0	10.07	12.6	3.23	6.0
165	0.7	-19.22	39.9	10.27	14.4	3.24	5.0
171	0.7	-19.05	43.2	9.95	15.5	3.25	4.0
177	0.7	-19.03	49.0	10.33	17.5	3.27	6.0
179	0.7	-18.64	48.6	10.40	16.9	3.35	4.0
182	0.7	-18.64	43.9	11.34	15.4	3.32	5.0
186	0.7	-19.21	50.1	9.99	17.6	3.32	5.0
187	0.7	-18.42	49.2	10.35	17.1	3.36	5.0
188	0.7	-19.33	42.3	9.60	15.1	3.27	4.0
190	0.7	-18.65	46.6	10.23	16.1	3.38	4.0
194	0.7	-18.67	44.8	11.22	15.8	3.31	4.0
195	0.7	-18.57	28.6	10.47	10.2	3.26	4.0

196	0.7	-18.75	43.9	10.06	15.8	3.24	6.0
197	0.7	-18.40	52.9	11.90	18.8	3.28	3.0
199	0.7	-19.62	45.5	10.10	16.3	3.26	6.0
199 QCD	0.7	-19.63	44.6	10.28	15.9	3.27	6.0
202	0.7	-18.91	46.8	10.95	16.6	3.29	5.0
203	0.7	-18.77	40.5	11.46	14.3	3.31	1.0
205	0.7	-18.57	44.3	10.81	15.8	3.27	4.0
206	0.7	-19.38	38.7	9.51	13.7	3.30	4.0
208	0.7	-19.10	49.5	10.56	17.6	3.28	4.0
212	0.7	-17.75	45.7	8.32	16.4	3.25	5.0
213	0.7	-19.49	51.4	10.58	18.4	3.26	4.0
216	0.7	-19.08	44.2	10.24	15.5	3.33	4.0
218	0.7	-18.86	45.8	10.19	16.1	3.32	6.0
219	0.7	-18.11	55.5	11.15	19.2	3.37	4.0
222	0.7	-19.05	37.2	10.43	13.1	3.30	5.0
223	0.7	-18.57	51.7	10.67	18.4	3.28	6.0
223 QCD	0.7	-18.51	45.0	10.53	16.1	3.26	6.0
224	0.7	-18.95	51.1	10.41	18.3	3.26	4.0
225	0.7	-18.57	42.0	10.34	14.9	3.29	5.0
226	0.7	-18.41	50.6	10.88	17.7	3.33	9.0
226 QCD	0.7	-18.44	43.1	10.74	15.3	3.28	9.0
227	0.7	-19.23	44.6	10.63	16.1	3.23	5.0
228	0.7	-17.96	44.4	11.61	15.8	3.28	6.0
229	0.7	-17.55	51.4	11.92	18.4	3.26	7.0
229 QCD	0.7	-17.49	38.2	11.80	13.6	3.27	7.0
231	0.7	-18.72	31.6	9.99	11.4	3.23	5.0
232	0.7	-19.16	40.9	9.96	14.6	3.26	4.0
233	0.7	-18.56	44.4	10.57	15.9	3.26	5.0

235	0.7	-19.14	50.1	11.72	17.4	3.36	9.0
238	0.7	-19.29	47.3	10.22	16.8	3.28	4.0
241	0.7	-19.34	42.7	9.49	15.1	3.30	4.0
243	0.7	-18.57	36.7	10.82	13.1	3.27	6.0
245	0.7	-19.18	38.3	10.51	13.6	3.28	5.0
246	0.7	-18.90	47.5	10.11	17.0	3.26	8.0
248	0.7	-19.06	46.0	10.47	16.3	3.29	6.0
251	0.7	-18.51	43.3	11.73	15.5	3.26	4.0
252	0.7	-18.99	52.6	10.01	18.9	3.25	2.0
253	0.7	-18.71	50.7	10.78	17.6	3.36	6.0
257	0.7	-19.02	48.2	10.63	17.2	3.27	7.0
258	0.7	-18.54	49.3	11.26	17.6	3.27	4.0
259	0.7	-18.76	35.2	10.27	12.7	3.24	5.0
260	0.7	-18.85	44.2	10.04	15.7	3.28	4.0
261	0.7	-19.02	42.3	10.18	14.9	3.32	5.0
264	0.7	-18.97	28.5	10.62	10.1	3.28	3.0
265	0.7	-17.97	42.1	10.64	14.9	3.30	9.0
265 QCD	0.7	-17.92	45.4	10.58	16.0	3.31	9.0
266	0.7	-18.33	48.0	11.75	16.8	3.33	7.0
268	0.7	-18.67	43.2	11.28	15.4	3.27	3.0
269	0.7	-18.91	36.9	10.21	13.2	3.26	4.0
270	0.7	-18.33	50.2	10.60	18.0	3.25	4.0
271	0.7	-18.82	39.6	10.50	13.9	3.32	4.0
272	0.7	-19.25	41.4	10.47	14.8	3.26	6.0
272 QCD	0.7	-19.30	31.6	10.39	11.3	3.27	6.0
280	0.7	-17.96	43.3	11.16	15.4	3.28	4.0
281	0.7	-18.25	36.2	11.04	13.0	3.25	6.0
281 QCD	0.7	-18.24	34.5	11.29	11.3	3.27	6.0

282	0.7	-18.90	40.9	10.28	14.5	3.28	6.0
283	0.7	-18.28	44.4	10.64	15.8	3.28	9.0
284	0.7	-19.08	41.1	9.96	14.6	3.29	7.0
285	0.7	-19.07	45.6	10.57	16.2	3.28	4.0
286	0.7	-18.47	54.6	10.91	19.5	3.27	6.0
287	0.7	-19.13	43.7	9.45	15.4	3.31	4.0
289	0.7	-18.83	48.4	10.60	17.3	3.26	6.0
290	0.7	-18.33	52.2	10.24	18.6	3.27	9.0
293	0.7	-18.56	46.8	10.38	16.5	3.31	5.0
294	0.7	-19.31	58.6	9.78	20.9	3.27	5.0
297	0.7	-18.29	56.9	11.38	20.5	3.24	5.0
298	0.7	-18.58	50.4	11.81	17.7	3.32	4.0
299	0.7	-18.11	57.8	10.73	20.7	3.26	8.0
305	0.7	-18.25	44.9	10.99	15.8	3.31	5.0
306	0.7	-18.19	45.2	10.60	15.9	3.32	4.0
307	0.7	-18.28	40.6	10.76	14.6	3.25	7.0
308	0.7	-18.01	49.1	11.29	17.3	3.31	5.0
309	0.7	-18.45	51.4	10.55	18.0	3.33	5.0
310	0.7	-18.83	51.2	10.48	17.7	3.37	5.0
314	0.7	-19.26	20.2	9.91	7.2	3.29	5.0
315	0.7	-19.01	60.9	10.84	21.7	3.27	6.0
316	0.7	-18.78	27.4	10.50	9.8	3.27	7.0
317	0.7	-18.70	44.5	10.05	16.0	3.24	4.0
318	0.7	-19.49	44.5	10.99	15.7	3.31	4.0
319	0.7	-18.79	50.5	10.61	17.7	3.33	4.0
321	0.7	-18.33	53.1	11.28	18.5	3.35	5.0
322	0.7	-18.67	47.2	10.77	16.5	3.34	4.0
323	0.7	-18.02	51.1	11.09	17.9	3.33	6.0

324	0.7	-18.49	46.4	10.41	16.7	3.24	5.0
327	0.7	-18.62	31.7	9.33	11.3	3.27	6.0
328	0.7	-18.85	62.3	9.73	22.2	3.27	5.0
328 QCD	0.7	-18.82	48.7	9.57	17.5	3.25	5.0
330	0.7	-18.63	41.8	9.88	14.9	3.26	4.0
334	0.7	-18.21	35.7	10.98	12.8	3.26	6.0
336	0.7	-18.61	44.2	10.75	15.7	3.28	8.0
336 QCD	0.7	-18.55	47.7	10.91	16.8	3.3	8.0
338	0.7	-18.67	37.3	9.80	13.3	3.27	4.0
340	0.7	-18.35	43.0	10.72	15.2	3.30	6.0
341	0.7	-17.95	45.2	10.70	16.1	3.27	9.0
344	0.7	-18.57	42.3	10.75	15.0	3.29	5.0
345	0.7	-18.30	49.6	10.97	17.3	3.34	4.0
346	0.7	-19.53	45.0	10.58	15.9	3.30	3.0
347	0.7	-19.88	44.4	10.02	16.0	3.24	4.0
349	0.7	-18.54	41.2	10.53	14.5	3.31	5.0
350	0.7	-18.79	42.2	10.62	15.1	3.26	5.0
353	0.7	-19.07	41.7	10.13	14.7	3.32	4.0
354	0.7	-19.12	42.1	10.02	15.1	3.25	4.0
355	0.7	-19.39	38.8	9.71	13.9	3.26	4.0
356	0.7	-18.66	52.5	10.62	18.9	3.24	5.0
358	0.7	-18.05	45.8	11.38	16.1	3.32	3.0
359	0.7	-19.08	44.6	11.42	16.0	3.25	3.0
360	0.7	-18.89	30.8	10.74	11.04	3.25	4.0
361	0.7	-18.78	46.1	10.45	16.6	3.24	5.0
362	0.7	-18.97	33.9	10.94	12.2	3.25	4.0
364	0.7	-19.07	46.2	10.44	16.4	3.29	5.0
365	0.7	-18.50	44.9	10.11	16.0	3.27	5.0

366	0.7	-18.61	55.0	10.41	19.8	3.24	5.0
367	0.7	-18.19	54.1	10.79	19.1	3.30	5.0
368	0.7	-18.29	52.9	11.24	18.9	3.26	4.0
369	0.7	-18.93	48.8	9.77	17.5	3.25	5.0
370	0.7	-19.02	41.3	9.81	14.7	3.28	4.0
374	0.7	-19.34	40.1	9.58	14.5	3.23	5.0
379	0.7	-18.85	49.2	9.81	17.5	3.28	4.0
380	0.7	-19.22	53.8	9.91	19.3	3.25	5.0
381	0.7	-18.34	16.0	9.67	5.6	3.31	4.0
384	0.7	-18.63	44.1	10.89	15.6	3.30	14.0
384 QCD	0.7	-18.63	47.0	11.08	16.6	3.3	14.0
385	0.7	-18.52	46.4	10.18	16.8	3.22	4.0
386	0.7	-18.28	50.4	12.1	17.7	3.32	8.0
388	0.7	-18.56	30.1	10.15	10.9	3.23	4.0
393	0.7	-19.46	29.6	10.58	10.6	3.25	4.0
396	0.7	-18.46	52.7	10.24	18.9	3.25	6.0
397	0.7	-19.45	56.0	9.72	19.5	3.35	14.0
397 QCD	0.7	-19.44	47.9	9.77	16.9	3.31	14.0
398	0.7	-19.05	46.5	10.83	16.4	3.31	5.0
399	0.7	-19.27	43.2	10.38	15.4	3.27	4.0
410	0.7	-17.97	55.0	12.38	19.3	3.32	6.0
411	0.7	-18.69	50.6	10.94	18.2	3.24	4.0
412	0.7	-18.57	45.6	11.35	16.3	3.26	5.0
414	0.7	-18.56	50.9	11.37	17.8	3.33	11.0
414 QCD	0.7	-18.56	35.2	11.32	12.5	3.3	11.0
415	0.7	-18.30	30.7	10.10	11.0	3.25	7.0
416	0.7	-17.67	51.5	12.11	18.6	3.23	6.0
417	0.7	-18.58	39.5	11.28	14.0	3.28	8.0

417 QCD	0.7	-18.58	49.8	11.39	17.7	3.28	8.0
418	0.7	-18.31	40.0	12.24	14.2	3.29	10.0
419	0.7	-18.13	42.9	11.63	15.3	3.27	6.0
421	0.7	-18.20	43.9	11.13	15.4	3.32	8.0
422	0.7	-18.35	42.0	10.77	14.9	3.30	3.0
429	0.7	-19.10	29.1	10.55	10.5	3.23	6.0
432	0.7	-18.81	45.8	10.41	16.3	3.28	4.0
434	0.7	-18.74	47.3	10.70	17.0	3.24	3.0
436	0.7	-18.99	44.2	10.15	15.8	3.26	4.0
439	0.7	-18.37	41.3	10.54	14.7	3.27	4.0
442	0.7	-19.29	32.2	11.00	11.5	3.27	5.0
443	0.7	-18.22	45.7	10.73	16.3	3.27	4.0
444	0.7	-19.03	52.1	10.49	18.3	3.32	4.0
445	0.7	-18.87	55.6	11.78	19.9	3.26	7.0
446	0.7	-18.45	42.5	11.96	15.2	3.26	4.0
448	0.7	-18.12	50.7	11.15	17.8	3.32	4.0
450	0.7	-19.32	43.0	11.04	14.3	3.51	5.0
451	0.7	-19.49	16.3	11.12	5.7	3.33	5.0
454	0.7	-18.27	34.0	11.40	12.2	3.25	3.0
455	0.7	-18.42	50.2	11.57	18.1	3.23	4.0
456	0.7	-18.11	48.1	11.38	17.3	3.24	5.0
457	0.7	-19.74	57.0	10.00	20.6	3.23	3.0
459	0.7	-19.01	51.9	10.27	18.3	3.31	4.0
460	0.7	-19.20	59.9	10.45	21.3	3.28	6.0
460QCD	0.7	-19.26	40.0	10.43	14.3	3.27	6.0
463	0.7	-18.69	37.7	10.50	13.6	3.24	5.0
464	0.7	-19.37	30.5	9.57	10.9	3.25	3.0
466	0.7	-19.61	47.2	11.12	16.8	3.28	3.0

467	0.7	-18.31	48.6	10.99	17.4	3.26	4.0
468	0.7	-18.50	48.1	11.84	17.1	3.28	4.0
469	0.7	-19.49	40.8	11.67	14.5	3.29	5.0
475	0.7	-19.61	34.7	10.09	12.2	3.33	4.0
477	0.7	-18.94	41.2	9.76	14.9	3.24	4.0
478	0.7	-18.95	42.4	11.25	15.4	3.21	3.0
480	0.7	-19.58	39.6	8.95	14.3	3.24	7.0
481	0.7	-18.97	47.1	10.70	16.5	3.33	5.0
484	0.7	-19.01	35.4	11.42	12.6	3.29	5.0
488	0.7	-19.19	41.6	9.97	14.9	3.25	6.0
489	0.7	-19.00	54.5	9.93	19.5	3.26	6.0
490	0.7	-19.60	39.2	10.44	14.0	3.27	7.0
491	0.7	-19.15	29.5	10.20	10.4	3.31	3.0
500	0.7	-18.17	47.6	11.81	16.8	3.30	3.0
511	0.7	-18.64	40.4	11.31	14.3	3.29	5.0
513	0.7	-18.70	46.0	10.41	16.6	3.23	4.0
517	0.7	-18.87	48.8	11.46	17.5	3.25	3.0
519	0.7	-18.42	46.8	12.14	16.9	3.23	5.0
525	0.7	-18.57	47.6	11.11	17.0	3.27	5.0
531	0.7	-18.20	46.6	10.70	16.4	3.31	5.0
535	0.7	-18.76	42.2	10.63	15.1	3.26	5.0
541	0.7	-19.49	43.6	9.42	15.6	3.26	4.0
54A	0.7	-18.57	40.5	11.35	14.5	3.26	8.0
62A	0.7	-19.05	44.7	10.25	16.1	3.24	5.0
62B	0.7	-18.85		10.22			5.0
NA (58)	0.7	-18.77	54.7	8.45	17.9	3.36	13.0

Martinšćica Faunal Values

Supplementary Table S4.12: Stable isotope results for Martinšćica faunal remains

Sample ID	Label	Bone	Weight (mg)	$\delta^{13}C$ (‰) vpdb	%wt C	$\delta^{15}N$ (‰) air	%wt N	Atomic C:N	Yield %
F1	Pig	Femur	0.7	-21.59	47.5	5.89	17.0	3.26	2.2
F2	Sheep	Femur	0.7	-21.40	35.5	4.98	12.5	3.30	2.3
F4	Dog	Femur	0.7	-18.84	52.3	8.79	18.9	3.23	3.2
F5	Goat	Femur	0.7	-21.05	36.8	5.60	13.2	3.25	3.7
F6	Horse	Occipital	0.7	-21.58	44.3	3.84	15.9	3.25	2.7
F7	Dog	Ulna	0.7	-18.29	54.7	11.24	19.4	3.29	5.8
F8	Goat	Ulna	0.7	-20.86	52.2	5.79	18.7	3.25	0.6
F9	Horse	Os Coxa	0.7	-21.74	54.1	3.77	19.3	3.27	1.8
F10	Horse	Lumbar Vertebra	0.7	-21.90	41.2	3.68	14.8	3.24	1.8
F11	Goat	Frontal	0.7	-20.70	46.3	4.50	16.5	3.27	3.2
F12	Goat	Os Coxa	0.7	-19.94	45.7	5.95	16.4	3.25	1.3
F13	Dog	Lumbar Vertebra	0.7	-19.24	51.6	8.92	18.6	3.24	0.7
F13 QCD	Dog	Lumbar Vertebra	0.7	-19.24	47.6	8.97	17.2	3.23	0.7
F14	Sheep	Ulna	0.7	-20.73	49.0	5.52	17.5	3.26	0.4
F14 QCD	Sheep	Ulna	0.7	-20.83	58.3	5.48	20.6	3.30	0.4
F15	Sheep	Os Coxa	0.7	-21.14	45.7	5.14	16.4	3.25	3.3
F16	Pig	Frontal	0.7	-20.61	43.1	5.08	15.8	3.18	1.3
F17	Pig	Cervical Vertebra	0.7	-20.99	36.1	6.36	12.8	3.28	1.9
F18	Pig	Os Coxa	0.7	-21.59	52.2	5.49	18.8	3.24	2.2
F19	Cattle	Thoracic Vertebra	0.7	-21.01	59.2	6.13	21.3	3.24	2.8

F20	Cattle	Humerus	0.7	-21.86	43.5	5.02	15.6	3.25	2.0
F21	Cattle	Metatarsal	0.7	-21.62	43.1	4.61	15.6	3.22	2.6

CHAPTER 5: DISCUSSION AND CONCLUSION

A syndemic analytical model require researchers to consider the broader epidemiological landscapes within which past peoples lived and how diseases/health-related conditions can influence and interact with one another within those systems. Not doing so can provide an incomplete and potentially skewed understanding of health, disease, and lived experiences in the past (Singer, 2009). As more integrative approaches analytical frameworks, like syndemic ones, gain traction in bioarchaeology and related fields, the primary purpose of this thesis was to explore: how applying this analytical framework shifts how we conceptualize and research health-related conditions and health data in bioarchaeological research; what approaches and methods can be leveraged to undertake this type of research more systematically; and how this approach can allow scholars to draw more and different information from our data. As such, my doctoral research had three objectives:

1. On a conceptual level, how does the application of a syndemic model shift the analytical frameworks employed in bioarchaeological research, and what are the implications of this for how we frame, structure, and conduct research on disease and health-related conditions within the field as a whole?
2. How can a syndemic model be applied to relevant research beyond historic epidemics to commonly analyzed interrelated health data, such as diet, nonspecific stress, and mortality risk, by leveraging multivariable statistical analyses?
3. How does applying this syndemic model allow us to glean more from commonly analyzed interrelated data?

5.1 BUILDING A SYNDEMIC BIOARCHAEOLOGY

As syndemic theory gains traction in bioarchaeology it is critical that researchers ensure that the analytical models their research is based upon align with the theoretical frameworks they are employing. The first paper in this thesis considered what applying syndemic theory to bioarchaeological research more broadly can look like. In Chapter 2, my co-author and I argue that applying syndemic theory in bioarchaeology requires transitioning from the often used traditional, discrete analytical models based on an approach of "isolate and analyze" to a more integrative, syndemic model that centers interconnection and interactions between health-related conditions. Analytical frameworks provide the foundation upon which research, including research questions, methods, and data collection, is constructed. Therefore, shifting our analytical frameworks has broad implications for research on health-related conditions in bioarchaeology beyond infectious diseases and past pandemics. Chapter 2 explores how applying a syndemic model in bioarchaeological research shifts our understanding of health-related conditions by emphasizing the significance of co-occurrence and interaction of health conditions, ultimately reshaping what we consider relevant to understanding their distribution and burden. In

doing so, it outlines how this transition raises new questions that have yet to be widely researched in bioarchaeology and related disciplines, like how the co-occurrence or interaction between health-related conditions can affect their skeletal manifestations, and what methods can be leveraged to undertake this type of research.

The review of extant research on co-occurrence, disease interaction, and syndemics demonstrates that the amount of research devoted to these topics is still relatively minor but growing. Research on co-occurrence and disease interaction is often limited to a single article, case study, or context (i.e., medieval England) and has not yet extended to comparative work examining differing patterns of co-occurrence or potential disease interaction across regions, sociohistorical contexts, and time. However, it provides the groundwork for such research. It should also be noted that while many studies take a discrete approach by focusing on a single condition—such as TB or syphilis—there is research that take a multi-scalar, regional, and temporal analyses of conditions that can serve as a foundation for exploring potential patterns of co-occurrence or interaction where syndemic, clinical, and bioarchaeological literature suggest it may exist (Roberts, 2008; van Doren, 2023; Zuckerman & Harper, 2016). Currently, most work on disease interaction and/or syndemics has concentrated on historic epidemics, including tuberculosis, influenza, and bubonic plague (Crespo et al., 2017; DeWitte & Slavin, 2013, p. 1918; DeWitte & Wood, 2008; Donoghue et al., 2005; van Doren & Sattenspiel, 2021). There is, therefore, significant potential to expand this type of research, as a syndemic analytical model is applicable to many conditions that bioarchaeologists analyze, including metabolic diseases, infectious diseases, bacterial diseases, trauma, diet, degenerative diseases, and nonspecific stress (see Chapter 2).

A syndemic model emphasizes that understanding the history, distribution, health outcomes, and burden of a disease or health-related condition often cannot be achieved by examining that condition in isolation, as has been the traditional approach. Researchers must consider how interactions with other diseases/health-related conditions within specific sociocultural environments may have significantly influenced and shaped these processes. This framework opens many new avenues of research around these topics. Operationalizing a syndemic model will require further research to understand how co-occurring or interacting health conditions affect the skeleton, as well as improved methods for identifying such co-occurrence in osteological samples. This can be achieved by integrating modern clinical literature to explore relationships between health conditions, as demonstrated by DeWitte & Bekvalac (2011) in their study of periodontitis and periosteal new bone formation; conducting immunological research to uncover biological mechanisms of interaction, as Crespo et al. (2017) did with inflammatory responses to TB and leprosy; and applying mixed methods—such as macroscopic and radiographic analysis—to known cases of co-occurrence, as shown by Schattmann et al. (2016) in their work on vitamin C and D deficiencies.

This raises new research questions about the relationships between health data, the contexts of interaction, the biocultural factors influencing it, and how these dynamics shape disease burden. As many health data that bioarchaeologists and others study are interrelated (see Chapters 2 and 3), designing research to be able to account for and/or incorporate the influence

and interaction of health data can provide more nuanced information on how and why variance occurred across regions or time (see Chapter 3), why and how health data varied (see Chapter 4), and the connection to larger biosocial environments (see Chapter 4).

The nature of osteological samples can create unique challenges to operationalizing a syndemic framework, including small sample sizes, fragmented/poorly preserved skeletal remains, limitations of how health-related conditions manifest skeletally, and difficulties establishing whether conditions temporally co-occurred. Despite this, Chapter 2 highlights how current research and methods can be leveraged to meet these challenges. Modern syndemic research clarifies the contexts and common combinations of interacting health conditions. Where available, archival and historical data can be used to help confirm the co-occurrence and interaction of specific health conditions (see Sawchuk et al., 2022) or complement analyses of skeletal data (see Perry & Gowland, 2022). Additionally, while establishing co-occurrence and disease interaction on an individual level is difficult, population-level approaches are a strength of bioarchaeological research that can be utilized here. Perry and Edwards's (2018) research on the diagnosis of vitamin C and D deficiency in a commingled sample highlights how bioarchaeology can use population-level studies to establish co-occurrence when it cannot be verified individually. Battles and Gilmour (2022) also remind us that conditions do not need to co-occur at the same time for processes of disease interaction to take place within biocultural contexts. Interaction can happen because of the long-term impacts of health-related conditions, such as impacts to the immune system, musculoskeletal system, etc., or mediated through socio-cultural contexts due to perceptions of stigma or lack of healthcare.

For methods, Crespo (2020) developed a skeletal inflammatory index (SINDEX) allowing researchers to examine systematic inflammatory reactions. When applicable, multivariate and multivariable analyses can account for the interplays between variables in analyses and examine interaction more directly (see Chapters 3 and 4). The results of Chapter 3 demonstrate the advantage of these statistical analyses compared to bivariate analyses and how they, in being able to control for the interaction and influence of health data on one another, can result in significantly different and more insightful data analyses. DeWitte (2015) argues that incorporating data on aDNA and parasitic infectious diseases can be particularly useful avenue to explore co-occurrence. Paleoepidemiological methods for differential diagnosis at the population level using sensitivity and specificity may also provide a useful method to begin to untangle skeletal expressions of disease and identify cases of possible co-occurrence (see Pedersen et al., 2019). Using multi-method approaches to record paleopathological indicators (i.e., macroscopic analysis, radiographs, CT imaging, etc.) can be used to diagnose and explore patterns of co-occurrence (see Morgan et al., 2024; Schattmann et al., 2016). One of the most effective ways to bridge gaps and explore disease interactions is through intra-, inter-, and trans-disciplinary research to more immediately and readily incorporate expertise across bioarchaeological and other disciplines. For example, this approach enables researchers to examine relationships—such as between infectious disease and trauma or co-occurrence with parasitic infections—that may lie outside their primary expertise, and effectively integrate relevant archival, paleoenvironmental, historical, and archaeological data.

5.2 SYNDEMIC MODELS AND MULTIVARIABLE STATISTICAL ANALYSES

Chapter 2 outlined how a syndemic model can be applied broadly in bioarchaeological research and identified multivariate/variable statistical analyses as one method to operationalize this framework. Diet, nonspecific stress, and mortality risk are commonly analyzed health data that are also closely interconnected through both social and biological processes (Juengst, 2018; Klaus et al., 2017; Scrimshaw, 2003; Singer, 2009). The results in Chapter 3 highlight how multivariable analyses can be leveraged to support the application of a syndemic model to bioarchaeological research on routinely collected data beyond the context of historic epidemics, enhancing interpretations of interrelated health factors and intra-population variation.

Multiple logistic regression analysis proved best suited for this research (Chapter 3). The data from Osor's osteological sample reflects the complexity of many bioarchaeological datasets: data was non-normally distributed, there was evidence of non-linear relationships between variables, data had unequal distributions (i.e., heteroscedasticity), and it included data that was diverse it terms of both type (i.e., categorical and continuous) and scale (i.e., years, per mil (‰), and count data). As such, multivariate/multivariable analyses that assume multivariate normality and homogenous variance, like principal components analysis, multiple linear regression, and MANCOVA, could not be readily applied. Multiple logistic regression analyses proved more flexible and inclusive because they do not assume normal distributions, homoscedasticity, or linear relationships between the predictor and outcome variables. It also allows multiple data types (i.e., continuous and categorical) to be incorporated into the analysis in addition to interaction terms. This type of multivariable statistical analysis shows promise for being flexible enough to handle the often complex and messy datasets in bioarchaeology and related disciplines.

The results of Chapter 3 outline the benefits and barriers when applying multivariable statistical approaches. The result of this study demonstrates that sample size and preservation are likely to be some of the most significant limiting factors to using multivariate or multivariable analyses (see Chapters 2 and 3). In this research, a little over half (n=196/341, 57%) of the individuals in the full sample had adequate preservation to allow them to be included in the multivariable analysis (Chapter 3). Additionally, the "full" sample (n=341) did not include those individuals whose skeletal remains were so poorly preserved that stable isotope analysis of rib collagen, paleopathological examination, or age-at-death estimation was completely impossible. Therefore, in the end, the multivariable sample only represents 35.6% (n=196/551) of the entire Osor osteological sample. In this case, this was still an adequate and representative sample size. However, it is likely that in many cases the smaller samples may not represent the larger sample, and higher rates of missing data may pose a more substantial challenge than they did here (Chapter 3).

As in this case, incorporating paleopathological and age-at-death data may also present unique challenges. Due to their nonspecificity, observations of the characteristics of nonspecific

pathological lesions (i.e., bone composition, size, etc.) are valuable for better understanding the biological processes they can reflect (Ragsdale, 1993; Ragsdale et al., 1981; Rinaldo et al., 2019). However, these data are often inherently correlated (i.e., the number of NSLs an individual has correlates with the number of bones with NSLs, etc.). As a result, these characteristics cannot all be included in logistic regression analyses without violating the assumption of non-multicollinearity. This issue extends to other paleopathological conditions, such as cribra orbitalia or porotic hyperostosis where recording methods, such as Rinaldo et al. (2019), collect data various characteristics of these porous lesions, such as severity or porosity and remodelling. Multicollinearity can distort results in various multivariable and multivariate analyses, not just in logistic regression, making it a critical consideration (Manly, 1986). This requires researchers to be selective and strategic in the types of data on nonspecific pathological conditions they incorporate into multivariate/multivariable analyses. In these cases, exploratory statistical analyses can be used to assess which variables are most significant within the context of the larger analysis (in this case, NSL size). Bivariate statistical analyses can also be used to supplement multivariable analyses when needed. However, differences in what these statistical analyses are based on (i.e., conditional probability vs mean differences) need to be considered. Wissler et al.'s (2022a, 2022b) work provides a guide for managing missing data.

Despite these hurdles, the results in Chapter 3 demonstrate how a syndemic approach to interrelated health data can lead to significantly different and more insightful understandings of these data. In this case, the differences between what was possible with bivariate and multivariable analysis were significant, substantially impacting how this data was ultimately interpreted (see Chapter 4). Part of these differences is undoubtedly due to the nature of these statistical analyses and what they are based upon. In this case, the bivariate analyses, including t-tests and ANOVAs, measure differences in mean values. Within the Osor sample, the data ranges for the different groups (i.e., cemetery and burial sectors) of the St. Peter's Cemetery sample often resulted in these groups having similar mean values despite differences in data distributions. Additionally, the unequal variance (i.e., heteroscedasticity) between groups in this sample (i.e., cemetery and burial sectors) violates t-tests and ANOVA's assumptions of homogenous variance. This can result in overestimations (Type I errors) or underestimations (Type II errors) of differences in analyses. In contrast, multiple logistic regression is based upon conditional probability and was better able to capture trends in the data that are not immediately evident in mean differences.

The ability of multivariable analyses to account for the interrelationships between dietary stable isotopes, nonspecific stress, and age-at-death resulted in significantly different outputs for which independent (predictor) variables were statistically significant, the degree of those differences, and how those variables differed between groups. This was often most evident in the binary multiple logistic regression results comparing the monastic and lay cemetery samples. Here, independent variables that were not statistically significant in the bivariate analyses (i.e., age-at-death and dietary stable isotope values) proved significant when analyzed simultaneously in the multivariable analysis. The impact of these variables for predicting cemetery group (i.e., monastic vs. lay) was also much greater in the binary multivariable analysis than was suggested by the bivariate results.

The multinomial logistic regression results comparing the different burial sectors agreed more with the bivariate analyses regarding which variables were significant and the degree of those differences. However, how dietary stable isotope values, nonspecific stress, and age-at-death appeared to vary differed between the two analyses. Multivariable analysis allows researchers to control for the impact of other variables in their analyses. For multiple logistic regression, the estimated marginal mean plots showed the probability of an individual belonging to the monastic or lay cemetery, or a specific burial sector, based on the value of the independent (predictor) variable when the other independent variables are held constant. This impacted how groups within the St. Peter's cemetery appeared to differ. While Sectors 4 and 6 had the greatest mean ages-at-death (53.3 and 50.3 years, respectively), the logistic regression results indicate that when other variables are controlled for, only Sector 6 differs significantly regarding age-at-death. Similarly, while Sector 4 has the lowest mean $\delta^{15}N$ values (i.e., 10.4‰), the logistic regression results indicate that the monastic group (Sector 4M) is likelier to have the lowest $\delta^{15}N$ values in the sample when other variables are controlled for.

In sum, the results of this analysis of Osor's medieval population demonstrates the benefit of operationalizing a syndemic analytical model through multivariable analyses to examine intra-population in the highly interconnected variables of diet, nonspecific stress, and age-at-death. The multivariable analysis reflected trends in the data that were not evident through bivariate analyses of mean difference and allowed for a more in-depth and nuanced data analysis. Importantly, while having more data helps with more multifaceted data analyses, the results of Chapter 3 demonstrate that simply integrating data on dietary stable isotopes, nonspecific stress, and age-of-death did not in itself result in a substantially more complex analysis. Rather, using multivariable statistical analyses, which can account for the interrelationships of data and their simultaneous impact on outcome variables, made a significant impact. While there are barriers, the thoughtful incorporation of multivariable and multivariate analyses alongside the continued development of new methods can help overcome the challenges posed by the nature of osteological samples.

5.3 WHAT DO WE LEARN WITH SYNDEMIC MODELS?

Singer (2009) argues that when health-related conditions are interrelated, discrete examinations can lead to incomplete and/or skewed understandings of data. The analysis in Chapter 2 outlines why this is the case and how it impacts bioarchaeological and related research. The results of Chapter 3 confirm that leveraging multivariable analyses to examine the simultaneous impact and variation of dietary stable isotopes, nonspecific stress, and age-at-death data within the Osor St. Peter's osteological sample resulted in significantly different interpretations. The final question of this thesis was how adopting such an approach allows us to glean more from commonly analyzed data. Chapter 3 highlights what more could be learned using a multivariable statistical approach. Chapter 4 delves into analyzing the results in their socio-historical context, highlighting what could be gathered from an integrative approach following syndemic disease models.

In contrast to the bivariate results, the binary multiple logistic regression results indicated that dietary stable isotopes, NSL characteristics, and age-at-death differed between the monastic and lay cemeteries. When the other variables were controlled, monastic individuals were likelier to have lower $\delta^{15}N$ values, higher $\delta^{13}C$ values, larger NSLs, and younger ages-at-death. The multivariable results also identified interactions between $\delta^{15}N$ values and NSL number and size. These results suggested more substantial differences between the monastic and lay populations at Osor. In contrast to other medieval European monastic communities at the time (Carić & Novak, 2024; Cirelli, 2013; Harvey, 1997; Janeš & Bedić, 2020; Mays, 2006; Novak, 2013; Rizner, 2017; Živaljević et al., 2019), St. Peter's monastic community, in the aggregate, did not have a notably "richer" diet (i.e., more protein-heavy) or diets that resembled those of the local elites. These results align with archaeological evidence suggesting that mollusks, which have lower $\delta^{15}N$ and higher $\delta^{13}C$ values, may have been a seasonal staple of St. Peter's monastic community (Rizner, 2017). These differences potentially highlight practices specific to St. Peter's monastery as a Camaldolese Benedictine order, which put greater emphasis on austere lifestyles, or differences between north-eastern Adriatic religious communities and those of inland Europe. Furthermore, in addition to having larger NSLs, monastic individuals were likelier to have younger ages-at-death, and those with larger and more NSLs were likelier to have higher $\delta^{15}N$ values. Together, these suggest differences in risk factors that likely connect to the different lifestyles between lay and monastic individuals. These data may reflect a greater risk for longer-term systemic stressors, such as metabolic conditions, that resulted in more and larger NSLs amongst this monastic community. The connection with $\delta^{15}N$ values suggests that there was a dietary component that differed from that seen in the lay sample, where individuals with more NSLs were likelier to have lower, rather than higher, $\delta^{15}N$ values.

In addition to the differences between the monastic and lay groups, medieval European burial practices were such that burial in specific areas within and around the church can often correlate with differences in status, kinship, and lineage (O'Sullivan, 2013). The results of the multinomial multiple logistic regression suggested a greater diversity in lived experiences across Osor's lay burial sectors than would be evident from the bivariate results. These data suggest that Osor's elite from burial sectors 1 and 5 had more protein and marine-rich diets characterized by higher $\delta^{15}N$ and $\delta^{13}C$ values. Dietary stable isotope data from known privileged burials in Sector 3 and the monastic cemetery (Sector 4M) confirm a connection between higher status and higher dietary stable isotope values across the sample. This aligns with historical data that suggests that some marine resources were considered prized dietary staples, although Osor's data does not indicate that these elite individuals regularly ate marine resources such as tuna, which are known to have been particularly prized and more expensive (Fabijanec, 2016). While elite diets reflect a more privileged lifestyle, individuals in both Sectors 3 and 5 exhibited distinct patterns of nonspecific stress and mortality risk that suggest higher degrees of frailty amongst these individuals. These burial sectors date more firmly to a tumultuous era in Osor's history (13^{th}-15^{th} centuries CE) where inhabitants would have experienced outbreaks of bubonic plague, invasion and violence due to war, and subsequent malaria outbreaks (Miladinov, 2008; Protić, 2015). The patterns of higher frailty may thus reflect the chronology of these burials. However, higher $\delta^{15}N$ values were also associated with lower ages-at-death in burial sectors whose chronology

extended across the cemeteries use (10^{th}-16^{th} centuries CE). As such, this may suggest specific risk factors associated with elite lifestyles in Osor.

In contrast, individuals from privileged and simple burials in Sector 6 were most likely to have the lowest $\delta^{13}C$ values across all burial sectors and lower $\delta^{15}N$ values compared to elite individuals in Sectors 1 and 5. This indicates that individuals in Sector 6 had a more terrestrial, protein-based diet compared to other lay burial sectors, suggesting different dietary patterns and relationships between diet and status. Individuals in Sector 6 also exhibited differing trends in age-at-death and were most likely to live to the oldest age categories. These results suggest that Sector 6 individuals stood out compared to the rest of Osor's lay cemetery and are perhaps worthy of further research and examination. Other stable isotope analyses, such as $\delta^{18}O$, that can help identify whether these individuals are from Osor or migrants to the area, may be of interest. Later centuries (13^{th}-15^{th} centuries CE) in the eastern Adriatic saw increases in migration (Ivetić, 2022; Mlacović, 2012). Some of the variation identified in this research may reflect some diversity due to migration and population movement, though this cannot be verified with these results. Lastly, the multinomial logistic regression results found differing relationships between dietary stable isotope values and age-at-death across the lay burial sectors. The types of proteins consumed might have varied or diminished with increased age in Sectors 4 and 6. Unfortunately, sample sizes and a lack of more chronological data mean that this cannot be firmly connected to differences in diet across the life course, heterogeneity within these groups, or potential differences stemming from chronology, as most burial sectors were in use for multiple centuries.

The results in Chapter 4 highlight a wealth of insights and connections to the socio-historical data made possible by operationalizing a syndemic analytical model to examine intra-population variation in interrelated health data. These results were able to highlight a diversity of lived experiences across Osor's population that would not have been recognized otherwise. In doing so, these results enabled stronger connections to be made between the historical and archaeological data and revealed apparent differences in dietary practices, nonspecific stress, mortality outcomes for Osor's monastic community compared to contemporaneous medieval European monastic communities. Additionally, the differing relationships between dietary isotope and paleopathological data for the monastic and lay groups potentially reflect how different biocultural processes shaped these interconnections.

5.4 FUTURE RESEARCH

Many future avenues of research were raised throughout this research. The analysis in Chapter 2 highlights the need for more research to develop methods to diagnose co-occurrence of health conditions, their expression in skeletal remains, and where, why, and how co-occurrence and interactions occur across varying socio-historical contexts. This will be invaluable research for expanding the application of syndemic analytical frameworks in bioarchaeological research. Furthermore, bioarchaeological and related research can offer valuable insights into how health

conditions interact today by deepening our understanding of their interrelationships across diverse socio-historical contexts in the past.

The results of Chapter 3 demonstrate the promise of multiple logistic regression to account for and examine interrelationships between health data in bioarchaeological and related research, where applicable. Future research can build upon this work and apply similar approaches in other contexts or to studying diet, nonspecific stress, and mortality risk in other osteological samples to explore how these relationships vary in other contexts. Conducting similar research on other contemporaneous osteological samples in this region can help build regional syntheses like has been done in paleoepidemiological research (Vlok & Buckley, 2022).

The results of Chapters 3 and 4 also identified further areas of inquiry for the Osor St. Peter sample. Future studies on the Osor sample regarding dietary stable isotopes, aDNA, $\delta^{18}O$ isotope data, metabolic disease, and burial chronology can help illuminate and clarify the trends identified here. Stable isotope data indicate that Osor's inhabitants generally had a mixed diet including both terrestrial and marine protein sources. Future stable isotope research employing Bayesian statistics could better clarify the ratio of marine and terrestrial protein in the diet, thereby enhancing clarity around dietary practices at Osor and how they varied across groups. Additional research utilizing aDNA or $\delta^{18}O$ isotope data can help determine whether those individuals in Sector 6 were locals or migrants and could clarify whether the variation seen among these individuals is a result of diverse lifestyles within Osor or possibly reflects diversity because of population movement. A paleopathological analysis of metabolic diseases could shed light on whether monastic individuals were at a higher risk for these conditions than individuals in the lay population. Lastly, future research aimed at refining the chronology for Osor St. Peter's burials could better clarify whether some of the variation across Osor's sample can be attributed to changes in lived experience over time. In particular, the patterns of frailty exhibited by lay individuals in Sectors 3 and 5 could help determine whether they can be more firmly associated with the tumultuous events throughout the 13^{th}-15^{th} centuries CE, or whether this reflects particular risk factors associated with elite lifestyles. This could also help clarify whether the connections between age-at-death and stable isotope values reflect dietary changes across the lifespan, or if this is a product of heterogeneity within the individual burial sectors.

5.5 CONCLUSIONS

As bioarchaeologists and related researchers increasingly adopt integrative frameworks like the syndemic model, the way we conceptualize and investigate health and disease in the past is fundamentally shifting. Because analytical frameworks shape our research questions, design, methods, and interpretations, this shift carries significant implications. By recognizing the interrelated nature of health data, researchers can design studies that more intentionally capture the complexities and interrelationships of the health-related conditions we study and enable more systematic and meaningful applications of syndemic theory across bioarchaeology and related disciplines.

In this thesis, I set out to demonstrate the utility and significance syndemic analytical models for bioarchaeological and related research generally. To do so, I first examined how the application of a syndemic analytical model significantly shifts how health-related conditions are conceptualized and what questions and data are considered significant for this type of research (Chapter 2). This outlined how the syndemic model raises and unlocks a wealth of new research questions, insights, and new data for bioarchaeology and related disciplines by shifting currently discrete, analytical frameworks. I then sought to demonstrate how syndemic analytical framework can be operationalized more broadly in bioarchaeological research and how this poses significant benefits for bioarchaeological and related research by allowing researchers to glean new and more nuanced insights from the types of health data that are already commonly studied.

By employing a syndemic framework and designing this research to be able to examine and account for the interrelationships between health-related conditions, a more dynamic picture of intra-population variation in the Osor osteological sample emerged. This research identified trends in diet, nonspecific stress, and mortality for Osor's monastic and lay population that were both convergent and divergent with larger regional trends in population health and sociocultural practices across the eastern Adriatic and Europe more broadly. This research revealed notable differences in dietary habits, indicators of nonspecific stress, and mortality risks between and within the monastic and lay communities. The results indicate that the dietary practices of Osor's monastic community, situated in a prominent center of religious reform, were significantly different from the elite lay population, and more closely resembled those of the broader lay population rather than elite diets in contrast to other medieval European monastic communities. Despite a higher occurrence of nonspecific lesions (NSLs) among monastic individuals, which was generally an indicator of resilience in this sample, this did not result in an overall reduced mortality rate, also contrasting with trends observed in other medieval monastic groups. This finding may suggest underlying vulnerabilities tied to the monastic lifestyle at Osor, potentially linked to chronic health issues. In comparison, while elite lay individuals had diets rich in marine resources, they did not experience the expected health advantages seen in other contemporaneous Croatian populations, as reflected in nonspecific stress patterns that suggest increased frailty rather than resilience.

Syndemic theory has underscored the considerable potential of shifting our analytical approaches. This research demonstrates how applying a syndemic framework to commonly studied bioarchaeological data—such as diet, stress, and mortality—can reveal more nuanced patterns of intra-population variation and clarify the biocultural processes shaping these patterns and shows how existing datasets can yield deeper insights when examined through an interaction-focused lens. In doing so, this research contributes a methodological and conceptual roadmap for future research, encouraging more intentional, integrative approaches to understanding health in the past.

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