ABSTRACT

Title of Dissertation:	THE BISHOP'S MEASURE: LOG-SCALED ANALYSIS OF LIVESTOCK SIZE AND MANAGEMENT AT SKÁLHOLT IN THE NORTH ATLANTIC CONTEXT
	Kevin S. Gibbons, Doctor of Philosophy, 2025
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This dissertation examines livestock management at Skálholt, an elite ecclesiastical center in early modern Iceland, through biometrical analysis of faunal remains. Applying log-ratio scaling to postcranial elements from cattle and sheep dated to the seventeenth and eighteenth centuries, this research identifies distinctive morphological patterns indicating specialized husbandry strategies. The cattle assemblage indicates evidence for beef-focused production through distinctive metacarpal dimensions and the presence of polled specimens, while sheep remains demonstrate specialized wether management for wool production with significant dimensional differences between length and width measurements. When situated within broader North Atlantic contexts, Skálholt's assemblage demonstrates a regionally specific approach to agricultural innovation distinct from contemporaneous English improvement patterns. Rather than wholesale adoption of continental models emphasizing dramatic size increases, Skálholt shows selective enhancement of

specific traits while maintaining adaptations to Iceland's environmental constraints. These findings challenge simplistic diffusion models of agricultural improvement and illuminate how elite institutions in peripheral regions mediated between local traditions and external influences during periods of agricultural transition.

THE BISHOP'S MEASURE: LOG-SCALED ANALYSIS OF LIVESTOCK SIZE AND MANAGEMENT AT SKÁLHOLT IN THE NORTH ATLANTIC CONTEXT

by

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Chapter 1: Introduction

1.1 Setting the Stage

The Icelandic bishopric of Skálholt served as one of Iceland's two episcopal seats from 1056 until the end of the eighteenth century, making it a major center of religious, political, and economic power throughout both the medieval and early modern periods. As one of Iceland's largest landowners, it controlled approximately 300 properties throughout its diocese, establishing itself as a central node in regional economic networks (Júlíusson et al. 2020; Lucas and Snæsdóttir 2022). The bishopric accumulated substantial landholdings through acquisitions, donations, and fines, collecting rents, tithes, and taxes in kind – including woollens – from its numerous tenant farmers. This extensive control over resources positioned Skálholt as a critical institution within Iceland's evolving social-ecological system during a period of significant agricultural transition across Europe.

This dissertation examines the faunal remains recovered from archaeological excavations at Skálholt, focusing specifically on biometrical analysis of sheep and cattle bones dated to the seventeenth and eighteenth centuries. Through systematic analysis of livestock morphology, this research addresses fundamental questions about agricultural adaptation, elite consumption practices, and potential engagement with broader European improvement movements in early modern Iceland. By situating these findings within comprehensive comparative frameworks spanning both time (from settlement to the post-medieval period) and space (across the North Atlantic region), this study illuminates how Skálholt negotiated the complex interplay

between environmental constraints, cultural traditions, and external influences during the early modern period.

The central research questions guiding this investigation include: Did livestock management at Skálholt demonstrate evidence of specialized practices distinctive from typical Icelandic farms? To what extent did this ecclesiastical center engage with broader European agricultural innovations? How did environmental constraints and institutional priorities shape livestock morphology at this elite site? And what can these patterns tell us about the relationship between elite status and agricultural adaptation in marginal environments? Through these questions, this dissertation contributes to our understanding of how an elite ecclesiastical center navigated environmental and economic challenges in the North Atlantic region during the early modern period.

The timeframe of this study – primarily the seventeenth and eighteenth centuries – represents a critical juncture in Iceland's environmental and sociopolitical history. This period coincided with significant agricultural transformations across Europe often associated with the "Second Agricultural Revolution" (Allen 1999; Kerridge 1967; Overton 1996), while in Iceland, it overlapped with the Danish Trade Monopoly (1602-1787), which fundamentally reconfigured economic relationships and resource exploitation patterns (Martin 2022; Róbertsdóttir 2014). Simultaneously, Iceland faced environmental challenges including pronounced climate fluctuations during the Little Ice Age, with marked variability affecting both terrestrial agricultural productivity and marine resource exploitation (Ogilvie 1992; Ogilvie and Jónsdóttir 2000). These intersecting factors created a complex context for agricultural

adaptation that makes Skálholt an especially valuable case study for investigating how elite institutions responded to environmental and economic pressures.

1.2 Historical Ecology as a Conceptual Framework

This dissertation employs historical ecology as its primary conceptual framework – an approach particularly well-suited to investigating the complex interrelationships between human activities and long-term environmental change. Historical ecology has developed in response to a more sophisticated understanding of complex adaptive systems and the various scales at which cultural and natural systems interact and respond to each other (Balée 1998; Crumley 1994). As a framework, it is characterized by the integration of archaeological, historical, ethnographic, environmental, and other appropriate data at the landscape scale (Balée and Erickson 2006; Crumley 2012; Meyer and Crumley 2011). This interdisciplinary investigation approaches human-environment interactions using models of complex adaptive systems, with an increasingly clear ability to provide results that are relevant to understanding contemporary issues involving social-ecological adaptation (Crumley 2021).

Among various frameworks concerned with the relationship between humans and nature, historical ecology emphasizes the complex interplay between human culture and the biosphere. This is achieved through empirical investigation of all cultural, biological, and geological facets of a region at specific temporal scales (Balée 1998). Historical ecology has connections with established frameworks such as cultural ecology and historical materialism, but assumes as its central principle that

people and the biosphere have continuous mutual influence over each other (Crumley 1994). While cultural ecology focused on a unidirectional effect of the environment on the development of culture, historical ecology identifies the relationship between nature and culture as fundamentally dialectical (Ingerson 1994).

Several key postulates underpin historical ecology as articulated by Balée (1998). First, human beings have affected the biological and geophysical systems of every region they have occupied, with virtually no truly "pristine" environments free from human influence. Second, human activity is not intrinsically destructive to environments or biodiversity – some human practices have increased biodiversity and environmental productivity in specific contexts. Third, different kinds of sociopolitical and economic systems can have varying effects on landscapes, with some systems capable of sustaining biodiversity while others dramatically reduce it. Fourth, human societies and the landscapes with which they interact can be studied as "total phenomena" through concepts drawn from various ecological and social sciences.

The landscape serves as the central unit of analysis in historical ecology, providing a conceptual space where ecological processes and human actions intersect (Crumley 1994). Landscapes act as palimpsests, with new human decisions and conflicts imprinted on the biosphere above earlier patterns of resource use and management (Balée and Erickson 2006; Berkes et al. 2000). By expanding the domain of study to the landscape, historical ecology allows engagement with human cognition – how communities perceive their environment and make decisions that ultimately manifest in the landscape itself. Landscapes become, in this framework,

not merely environmental backdrops but dynamic products of ongoing negotiation between human agency and ecological processes.

The temporal dimension is also critical to historical ecology, which draws heavily from the French Annales school of historical thought. This approach recognizes multiple temporalities operating simultaneously: the short-term event (*événement*), the medium-term conjuncture (*conjoncture*), and the long-term structural history (*longue durée*) (Crumley 1998). Archaeological evidence is particularly valuable for addressing the longue durée, providing insights into long-term human-environment relationships that may not be visible at shorter temporal scales. This multi-scalar temporal approach is especially relevant for understanding livestock morphology, which reflects both immediate management decisions and longer-term evolutionary processes.

Historical ecology provides a particularly suitable framework for examining livestock management at elite centers like Skálholt. Domestic animals represent a critical intersection between natural and cultural systems – their bodies bear the imprint of both biological processes and human selection decisions. The morphology of sheep and cattle thus serves as a physical manifestation of the dialectical relationship between human culture and the natural environment that stands at the core of historical ecology. By examining how these morphological patterns changed over time and differed across space, we can gain insights into the complex interplay between environmental constraints, cultural practices, and external influences that shaped agricultural adaptation in early modern Iceland.

1.3 The North Atlantic as a Laboratory for Historical Ecology

The North Atlantic region presents a particularly valuable laboratory for historical ecological research. With its islands, marginal environments, and well-documented history of human settlement, the region offers exceptional opportunities to investigate human-environment interactions across multiple temporal and spatial scales. The archipelagic geography creates natural boundaries for study, while the relatively recent human colonization (especially in Iceland and Greenland) provides clear baselines for examining anthropogenic environmental change. These factors, combined with the region's excellent preservation conditions and rich documentary record, have made the North Atlantic a focal point for historical ecological research (McGovern et al. 2007; Harrison and Maher 2014).

The North Atlantic Biocultural Organization (NABO) has played a pivotal role in coordinating historical ecological research across this region since its establishment in 1992. This international research cooperative has facilitated standardized recording protocols, comparative analyses, and collaborative approaches that have substantially advanced our understanding of human-environment relationships in the North Atlantic through time (McGovern et al. 2007). NABO research has produced detailed reconstructions of settlement patterns, land use strategies, and environmental change across the region, providing valuable comparative contexts for understanding the developmental trajectories of different North Atlantic communities. The vast majority of comparative data utilized in this dissertation are the product of decades of these shared data standards.

Iceland occupies a distinctive position within this regional framework. Its settlement in the late ninth century (c. 870 AD) by Norse colonists represents a well-documented example of human colonization of a previously uninhabited landscape (Schmid et al. 2017; Vésteinsson and McGovern 2012). This colonization process introduced northwestern European livestock, including cattle, sheep, goats, pigs, and horses, fundamentally altering the island's ecological dynamics (Dugmore et al. 2005). The ensuing transformation of Iceland's landscape through deforestation, grazing, and soil erosion has been extensively documented through archaeological and paleoecological research, providing detailed insights into the long-term consequences of human settlement (Dugmore et al. 2009; Streeter et al. 2015).

Research in Iceland has revealed complex patterns of adaptation and change in human-environment relationships from settlement through the early modern period. The initial colonization strategy attempted to impose familiar agricultural practices from northwestern Europe, but environmental realities soon forced adaptations (Eddudóttir et al. 2020; McGovern et al. in press). By the eleventh and twelfth centuries, Iceland's farming strategies had shifted significantly, with pigs and goats virtually disappearing from the zooarchaeological record and sheep becoming increasingly dominant in the livestock economy (Dugmore et al. 2012; McGovern et al. 2007).

The early modern period in Iceland saw further evolution in human-environment relationships. The establishment of the Danish Trade Monopoly in 1602 introduced new economic pressures, while climate deterioration during the Little Ice Age created additional challenges for agricultural production (Ogilvie and Jónsdóttir

2000; Dugmore et al. 2007). These intersecting factors necessitated ongoing adaptation in agricultural strategies, with implications for livestock management practices. The biometrical evidence from Skálholt provides a window into how one of Iceland's most powerful institutions navigated these challenges during a critical period of agricultural transition.

Previous historical ecological research in Iceland has laid important groundwork for the present study. Work by McGovern and colleagues (2007) on the "Landscapes of Settlement" project has documented the long-term consequences of Norse colonization in northern Iceland, while Hambrecht (2011, 2012) has explored specialized animal management practices at Skálholt during the early modern period. Simpson and colleagues (2001, 2004) have examined soil erosion patterns and their relationship to land management decisions, while Streeter and Dugmore (2014) have investigated landscape change through tephrochronology. This research has collectively established Iceland as a key case study in historical ecology, with particular value for understanding human adaptation to marginal environments.

The present study builds upon this tradition while focusing specifically on the biometrical evidence for agricultural adaptation at Skálholt during the early modern period. By examining livestock morphology at this elite ecclesiastical center within a broader comparative framework, this research contributes to our understanding of how institutions with substantial resources and European connections navigated the environmental challenges of the North Atlantic region. Skálholt thus provides a valuable case study for investigating how elite status influenced agricultural practices

and landscape management in a marginal island environment during a period of significant economic and environmental change.

1.4 Agricultural Adaptation and Livestock Management in Historical Context

Livestock have played a central role in shaping cultural landscapes across the North Atlantic region since initial settlement. As both biological organisms and cultural artifacts, domestic animals represent a nexus between natural processes and human decision-making. Their bodies bear the imprint of both environmental constraints and human selection, making them particularly valuable subjects for historical ecological research. Through zooarchaeological analysis, especially biometrical study, we can gain insights into how human societies managed these animals over time in response to changing environmental, economic, and cultural factors.

In Iceland, the introduction of domestic livestock during the settlement period (*Landnám*) transformed the island's ecosystem dynamics. Prior to human arrival, Iceland's biodiversity was characterized by limited diversity, with birch and willow woodland/scrub being the predominant vegetation in inhabited regions (Dugmore et al. 2005). The introduction of grazing animals, particularly sheep and cattle, led to widespread ecological changes through deforestation, overgrazing, and soil compaction, while also increasing biodiversity overall. These changes fundamentally altered the island's ecological character, creating new constraints and opportunities for human subsistence that would shape agricultural practices for centuries to come.

Livestock management in Iceland evolved significantly from settlement through the early modern period in response to these changing conditions. While earlier Viking Age sites maintained cattle-to-sheep ratios approaching 1:4, later medieval and post-medieval sites typically show ratios of 1:10 or higher, reflecting adaptation to Iceland's increasingly deforested landscape and challenging winter foddering requirements (McGovern et al. 2007, 2009). This shift toward sheep-dominated husbandry represented a pragmatic response to environmental constraints, as sheep could better utilize marginal grazing lands and required less winter fodder than cattle.

The management of livestock was further shaped by economic factors, particularly the role of wool in Iceland's economy. From the medieval period through the eighteenth century, woven wool cloth (*vaðmál*) served as a primary currency for both domestic and international transactions, facilitating tax payment, rent collection, and mercantile exchange (Róbertsdóttir 2008). During the Danish Trade Monopoly period (1602-1787), woollen products constituted Iceland's second most valuable export commodity after fish and meat products, with Danish authorities implementing systematic initiatives to enhance sheep farming efficiency, improve wool yields, and standardize production quality (Róbertsdóttir 2014).

Elite institutions like Skálholt played particularly significant roles in livestock management. As one of Iceland's largest landowners, Skálholt functioned as a central node in regional economic networks, collecting substantial rents and tithes in kind from its numerous tenant farmers (Júlíusson et al. 2020). This institutional context created conditions where specialized livestock management practices could emerge,

potentially reflecting both adaptation to Iceland's challenging environment and engagement with broader European agricultural developments. The biometrical evidence from Skálholt thus provides a window into how elite status influenced animal husbandry during the early modern period.

The potential for agricultural innovation at Skálholt is further suggested by documentary evidence. The agricultural manual *Atli* by Björn Halldórsson, composed in the late eighteenth century, explicitly engaged with contemporary European agricultural improvement discourse (Halldórsson 1948, in Hambrecht 2011). While this text postdates much of the Skálholt assemblage analyzed here, it reflects an intellectual environment where agricultural improvement was valued and pursued. More direct evidence comes from palynological analysis documenting a significant spike in barley pollen in seventeenth-century soil samples from Skálholt, suggesting experimental cultivation efforts at this ecclesiastical center (Einarsson 1982).

Biometrical analysis provides a particularly valuable approach for examining agricultural adaptation through livestock morphology. By systematically measuring animal bones according to standardized protocols, we can identify patterns and variations that reflect both intrinsic biological factors (like sex, age, and breed) and extrinsic influences (including nutrition, environment, and human selection). These patterns can reveal changes in animal management strategies over time, differences between sites reflecting varying status or economic priorities, and potential evidence for selective breeding or improvement efforts.

For cattle, biometrical analysis can help identify specialized management practices focused on meat production, dairying, or traction, while also potentially

revealing evidence for imported stock or selective breeding. For sheep, it can illuminate specialized wool production strategies through the identification of wethers (castrated males), which typically develop distinctive morphological characteristics. These insights allow us to reconstruct management decisions that might not be visible through other lines of evidence, providing a more complete picture of agricultural adaptation in early modern Iceland.

By situating this biometrical evidence within broader historical and environmental contexts, this dissertation examines how Skálholt's livestock management practices reflected its position as an elite ecclesiastical center with substantial resources and European connections. Through comparative analysis with other Icelandic sites and materials from across the North Atlantic region, we can evaluate whether Skálholt represents continuity with traditional Icelandic practices or innovation potentially reflecting broader European agricultural currents during this period of significant transition.

1.5 Research Design and Methodological Approach

This dissertation employs biometrical and statistical methodological approaches that integrates zooarchaeological analysis to address questions about livestock management and agricultural adaptation at Skálholt. At its core, this research relies on detailed biometrical analysis of sheep and cattle remains recovered during archaeological excavations at the site between 2002 and 2007 (Lucas and Snæsdóttir 2022). These excavations yielded substantial faunal assemblages comprising roughly 140,000 bone fragments, with more than 26,000 specimens

identified to species level (Hambrecht et al. forthcoming). The biometrical analysis focuses specifically on material from the seventeenth and eighteenth centuries, allowing examination of livestock morphology during a critical period of agricultural transition.

The methodological foundation for this research rests on standardized zooarchaeological protocols that facilitate comparative analysis across different sites and assemblages. Bone measurements follow von den Driesch (1976), while tooth eruption and wear recording follows Grant (1982). All data were recorded in the NABONE system developed by the North Atlantic Biocultural Organization, ensuring methodological consistency with other research in the region. This standardization is particularly important for the comparative aspects of this study, which examines material from multiple sites across Iceland and the broader North Atlantic.

To address challenges related to sample size and comparability, this research employs log-ratio scaling techniques that allow different measurements to be merged and plotted on the same scale. This approach, pioneered by Simpson (1941) and further developed by Meadow (1999), involves comparing archaeological specimens to a standard reference, calculating the logarithm of the ratio between the archaeological measurement and the equivalent standard measurement. For sheep, the reference standard used is a set of mean measurements from adult male Soay sheep (Clutton-Brock et al. 1990), while for cattle, measurements from a Bronze Age cow from Catalonia are employed (Nieto-Espinet 2018).

The log-ratio technique is particularly valuable for analyzing North Atlantic assemblages, where sample sizes for individual elements are often limited. By

converting measurements to dimensionless values relative to standard reference specimens, this approach facilitates the pooling of different skeletal elements to increase sample sizes while maintaining analytical rigor. Importantly, length and width dimensions are analyzed separately to identify potential differences in growth patterns that might reflect factors like castration, nutritional status, or selective breeding.

Complementary approaches employed in this research include withers height estimation and slenderness indices. Withers height provides an intuitive measure of livestock stature that complements the more abstract log-ratio values, facilitating cross-site comparisons and broader contextual interpretations (Teichert 1975; von den Driesch and Boessneck 1974). Slenderness indices offer insights into proportional relationships between length and width dimensions that can help identify potential castration effects and breed characteristics. Age profiles based on tooth eruption and wear provide contextual information about culling patterns that can illuminate management priorities related to meat, milk, wool, or traction use.

The comparative framework for this research operates at multiple scales. At the site level, it compares material from different contexts within Skálholt, particularly between elite household areas and midden deposits, to identify potential variations in consumption patterns. At the regional level, it compares Skálholt with other Icelandic sites spanning the settlement period through the post-medieval era, including early settlements like Sveigakot and Hrísheimar, the high-status farm at Hofstaðir, the trading center at Gásir, and the ecclesiastical estate at Möðruvellir. At the broadest scale, it incorporates material from Norse Greenland and Old Scatness in

Shetland, as well as contemporaneous English material from The Shires, to situate Skálholt within broader North Atlantic and European contexts.

This multi-scalar comparative approach allows examination of how livestock morphology at Skálholt related to both local Icelandic traditions and broader European agricultural developments in the wake of the "long" sixteenth century. By comparing dimensions, proportions, and variability across different sites and regions, we can identify patterns that might reflect environmental adaptation, cultural traditions, or innovative practices potentially linked to elite status and European connections.

Statistical analysis plays a crucial role in this research. Normality testing through methods like the Shapiro-Wilk test (Shapiro and Wilk 1965) and assessment of variance homogeneity using Levene's test (Levene 1960) inform the selection of appropriate analytical approaches. When assumptions of normality and homogeneity of variance are met, parametric tests like ANOVA are employed, followed by post-hoc comparisons using techniques such as Tukey's Honest Significant Difference test (Fisher 1925; Tukey 1949). For datasets that violate these assumptions, non-parametric alternatives like the Kruskal-Wallis test (Kruskal and Wallis 1952) provide robust alternatives, often followed by pairwise Wilcoxon rank-sum tests (Wilcoxon 1992) or Dunn's test with Benjamini-Hochberg correction (Benjamini and Hochberg 1995; Dunn 1964) for multiple comparisons.

Through this integrated methodological approach, combining standardized zooarchaeological protocols with sophisticated statistical analysis and robust comparative frameworks, this dissertation examines how livestock morphology at

Skálholt reflects the complex interplay between environmental constraints, cultural traditions, and elite status during the early modern period. This approach aligns with the interdisciplinary ethos of historical ecology, integrating multiple lines of evidence to develop a more holistic understanding of human-environment relationships in the past.

1.6 Significance of the Study

This dissertation makes several significant contributions to our understanding of historical ecology, agricultural adaptation, and elite management practices in early modern Iceland. By focusing on livestock morphology at Skálholt, it provides insights into how one of Iceland's most powerful ecclesiastical institutions navigated the complex interplay between environmental constraints, cultural traditions, and external influences during a period of significant agricultural transition. These insights have implications that extend beyond the specific case study to address broader questions about human-environment interactions in marginal environments.

First, this research contributes to our understanding of elite agricultural management in challenging environments. Elite institutions like Skálholt controlled substantial resources and maintained connections to broader European networks, potentially allowing them to implement specialized management practices beyond the capabilities of ordinary farms. By examining how these advantages manifested in livestock morphology, this study illuminates the relationship between social status and agricultural adaptation in early modern Iceland. This has relevance for

understanding how elite institutions functioning in similar marginal environments might have mediated between local traditions and external innovations.

Second, this dissertation provides insights into the selective adaptation of European agricultural innovations in peripheral regions. The early modern period witnessed significant agricultural transformations across Europe, often associated with the "Second Agricultural Revolution" (Allen 1999; Kerridge 1967; Overton 1996). However, the specific manifestation of these changes likely varied across different environmental and cultural contexts. By examining whether Skálholt's livestock show evidence of engagement with broader European currents of agricultural improvement, this study contributes to our understanding of how innovation diffused across geographical and cultural boundaries during this transitional period.

Third, this research advances our understanding of resilience and adaptation in social-ecological systems. Iceland represents an example of a coupled human-natural system, where human activities and environmental processes have continuously influenced each other since initial settlement (McGovern et al. 2007). By examining how livestock management evolved at an elite center during a period of significant economic and environmental challenges, this dissertation provides insights into the factors that enable resilience in marginal environments. These insights have potential relevance for contemporary discussions about sustainability and adaptation to environmental change.

Fourth, this study demonstrates the value of biometrical analysis for addressing historical ecological questions. By systematically analyzing livestock

morphology through standardized measurements, it shows how animal bodies can serve as archives of human decision-making and environmental adaptation. This methodological approach provides a model for integrating zooarchaeological data with broader historical and environmental contexts to develop more holistic understandings of past human-environment relationships.

Fifth, this dissertation contributes to the growing body of historical ecological research in the North Atlantic region. Building on previous studies of landscape change, settlement patterns, and environmental impacts (Dugmore et al. 2009; McGovern et al. 2007; Streeter and Dugmore 2014), it adds detailed insights into livestock management at a major ecclesiastical center during the early modern period. These findings enrich our understanding of how different communities across the North Atlantic region adapted to their distinctive environmental challenges while maintaining connections to broader European networks.

Finally, this research has potential relevance for contemporary issues related to agricultural sustainability and environmental management. By examining how past societies navigated the complex interplay between environmental constraints, cultural traditions, and economic pressures, it provides historical perspectives that could inform current efforts to develop more sustainable agricultural practices in marginal environments. While direct application of historical lessons requires careful consideration of contextual differences, the long-term view provided by historical ecology can help identify both successful adaptations and problematic patterns that might inform present decision-making.

1.7 Structure of the Dissertation

This dissertation is organized into seven chapters that progressively develop its argument about livestock management and agricultural adaptation at Skálholt. Following this introduction, which has established the conceptual framework, research questions, and methodological approach, the subsequent chapters examine different aspects of the evidence for specialized livestock management at this elite ecclesiastical center during the early modern period.

Chapter 2 presents the theoretical foundations of biometrical analysis in zooarchaeology. It explores how measurement of animal bones can provide insights into questions about domestication, husbandry practices, and environmental adaptation. This chapter situates the present study within broader methodological traditions while addressing the specific challenges and opportunities of biometrical analysis in North Atlantic contexts. It concludes by establishing the theoretical framework for interpreting biometrical patterns in the subsequent analysis.

Chapter 3 examines the biological and environmental factors that shape domestic mammal morphology. It provides a comprehensive overview of how both intrinsic factors (like sex, age, and breed characteristics) and extrinsic factors (including environment, nutrition, and human management practices) influence skeletal development in livestock. This discussion creates an essential foundation for distinguishing between different causal factors when interpreting the morphological patterns observed in the Skálholt assemblage.

Chapter 4 presents the social and environmental history of Iceland from settlement through the early modern period. It traces the transformation of Iceland's

landscape following Norse colonization, examining how human activities and environmental processes have continuously influenced each other over the millennium of settlement. This chapter pays particular attention to the early modern period, when the Danish Trade Monopoly and climate fluctuations created new challenges for agricultural production. It concludes with an overview of Skálholt's archaeological context, establishing the site's significance within Iceland's social and economic landscape.

Chapter 5 outlines the laboratory methods employed in this research. It describes the Skálholt assemblage and comparative materials from other sites, detailing the measurement protocols, log-ratio techniques, and statistical approaches used to analyze this material. This chapter also introduces the comparative framework spanning multiple sites across Iceland and the broader North Atlantic region, explaining how these comparisons will address questions about specialized management practices and potential agricultural improvement at Skálholt.

Chapter 6 presents the results of the biometrical analysis. It begins with an examination of the Skálholt assemblage, identifying distinctive patterns in both cattle and sheep remains that might reflect specialized management practices. It then situates these findings within progressively broader comparative contexts: first comparing different areas within Skálholt, then examining chronological changes across Icelandic sites, and finally incorporating material from across the North Atlantic and contemporaneous English assemblages. Through this multi-scalar approach, it identifies patterns that suggest both continuity with Icelandic traditions and potential engagement with broader European agricultural developments.

Chapter 7 discusses the implications of these findings and concludes the dissertation. It interprets the biometrical evidence within its historical and environmental context, examining how Skálholt's elite status, ecclesiastical function, and European connections influenced its livestock management practices. This chapter situates these findings within broader discussions of agricultural innovation, environmental adaptation, and the role of elite institutions in mediating between local traditions and external influences during periods of agricultural transition. It assesses the methodological strengths and limitations of the approaches employed, explores the theoretical implications of the research, and suggests potential directions for future investigations building on these insights. The chapter concludes by summarizing the key findings and their significance for understanding agricultural adaptation, institutional management, and human-environment interactions in marginal environments.

Chapter 2: Biometrical Analysis in Zooarchaeology

Biometrical analysis constitutes a foundational methodological approach within zooarchaeology, having evolved from primarily descriptive applications into sophisticated analytical frameworks that address complex questions regarding human-animal relationships throughout antiquity. The systematic measurement and statistical analysis of faunal remains provides critical insights into domestication processes, animal husbandry practices, environmental adaptation, and cultural exchange networks – dimensions of past human activity that might otherwise remain obscured in the archaeological record.

As Albarella (2002) observed, biometry has occasionally been "reduced to a bland and merely descriptive exercise in too many archaeological works," highlighting the necessity for more robust analytical frameworks that effectively connect biometrical patterns to broader archaeological questions. This critique reflects a persistent methodological tension within the discipline, as researchers negotiate the space between descriptive documentation and interpretive analysis. Contemporary approaches to zooarchaeological biometry have increasingly emphasized the integration of multiple evidential lines, sophisticated statistical methodologies, and nuanced theoretical frameworks that situate morphological patterns within their broader cultural and environmental contexts.

This chapter examines the theoretical foundations and methodological applications of biometry in zooarchaeological research, with particular attention to its relevance for understanding livestock morphology in the North Atlantic context. By

situating the present study within established methodological traditions, this discussion illuminates both the analytical potential and interpretive challenges of biometrical analysis for addressing questions about past human-animal relationships in marginal environments like Iceland.

The application of biometrical methods in zooarchaeology typically addresses three overlapping domains of inquiry: genetic issues (including species identification, domestication, and breed development), economic issues (relating to animal husbandry practices and management strategies), and environmental issues (examining adaptations to landscape and climatic conditions). While these categories provide a useful organizational framework, it is essential to recognize that disentangling the relative influence of genetics, environment, and human management on animal morphology presents significant interpretive challenges that necessitate sophisticated methodological approaches.

2.1 Theoretical Foundations of Biometrical Analysis

The use of biometry in zooarchaeology involves, at the most fundamental, the systematic measurement of animal bones and teeth according to standardized protocols, followed by statistical analysis of these measurements to identify patterns and variations within and between assemblages. The theoretical underpinnings of this approach are drawn from multiple disciplines, including zoology, anatomy, statistics, and archaeology, creating a methodological domain that is inherently interdisciplinary (Orton 2020; Tourigny and Gordon 2023).

The development of biometrical analysis in zooarchaeology was significantly influenced by early work in comparative anatomy and zoology, which established the importance of measurement for understanding taxonomic relationships and morphological variation (Albarella 2017). Von den Driesch's (1976) standardization of measurement protocols provides a shared methodological foundation as a near-universal standard, facilitating comparative analysis across different researchers and assemblages.

With the emergence of processual archaeology in the 1960s and 1970s and its emphasis on systemic approaches, experimental work, and middle-range theory, the disciple of zooarchaeology experienced a shift in methodological focus (O'Brien et al. 2005). This theoretical reorientation privileged certain methodological domains, such as taphonomy and butchery analysis, particularly within North American zooarchaeological traditions (Albarella 2002). However, European research traditions, particularly in German-speaking regions, maintained stronger continuity in biometrical analysis through the work of scholars like Boessneck (1969) and von den Driesch (1978), who consistently advocated for the value of metric data in addressing archaeological questions (Meadow 1999).

The explanatory utility of biometrical analysis has been further strengthened by developments in biological theory related to animal morphology. Understanding the complex factors that influence skeletal development – such as genetics, nutrition, mechanical stress, and hormonal regulation – provides a path to interpreting biometrical patterns in archaeofaunal assemblages (Reitz and Ruff 1994). This framework helps researchers distinguish between different causal factors affecting

morphology, such as differentiating genetic change from environmental response or identifying the skeletal signatures of specific management practices like castration (Albarella 1997b).

2.2 Methodological Approaches to Sample Size Challenges

2.2.1 The Scale Challenge and Scaling Techniques

One persistent challenge in zooarchaeological biometry is the limited sample size of many faunal assemblages. As Albarella (2002) notes, the vast majority of archaeological excavations do not produce high quantities of identifiable animal bone and thus do not produce robust zooarchaeological datasets, a situation exacerbated by commercial archaeology's time constraints and the relatively small percentage of excavated bones that can be reliably measured (Evin et al. 2023). This challenge has led to the development of innovative methodological approaches, particularly the application of scaling techniques (Meadow 1999; Wolfhagen 2020).

Size index scaling techniques, which allow different measurements to be merged and plotted on the same scale, have a long history in zooarchaeology. Initially described by Ducos (1968) and subsequently developed by Uerpmann (1979) and Meadow (1981), these approaches have become increasingly sophisticated. The fundamental principle involves comparing archaeological specimens to a standard reference, calculating the logarithm of the ratio between the archaeological measurement and the equivalent standard measurement (Simpson 1941).

Meadow (1999) defined these approaches as "size index scaling techniques," which have proven particularly valuable in Near Eastern zooarchaeological research. The effectiveness of this approach has been demonstrated in numerous early applications, including Meadow's (1984) work identifying size reduction in cattle, sheep, and goat during the Neolithic period at Mehrgarth (Baluchistan). Using the logarithmic scaling approach, Vigne and colleagues (2000) noted that pigs from an eighth millennium BC site in Cyprus were significantly smaller than their wild relatives on the Near East mainland, providing critical evidence for early livestock domestication (Davis 1981; Zeder et al. 2006).

At the turn of the millennium, Albarella (2002) made the case for more utilization of biometrical techniques in British zooarchaeology. The relatively limited application of scaling techniques in European contexts represents a missed opportunity, Albarella argued at the time, to maximize the interpretive potential of small assemblages, particularly given that a survey of animal bone reports from central England revealed that only 30% provided any biometric information (Albarella 2002).

2.2.2 Methodological Considerations in Scaling Applications

The implementation of scaling techniques requires careful methodological consideration. Several important factors that must be addressed:

Differential bone responses. Bones and teeth exhibit different growth patterns and responses to environmental factors, with teeth typically being more conservative and less affected by environmental conditions than post-cranial elements (Degerbøl

1963; Payne and Bull 1988). Combining bones and teeth in scaling analyses may therefore obscure important patterns of variation.

Dimensional variation. Different measurement dimensions (lengths, widths, depths) may respond differently to environmental and genetic factors. For instance, Davis (1996) demonstrated that sheep post-cranial measurements vary similarly when measured along the same axis, but this pattern does not hold when comparing lengths, widths, and depths. Consequently, these dimensions should be analyzed separately whenever possible (Grau-Sologestoa et al. 2021).

Measurement variability. Not all measurements exhibit equal variability. Elements that fuse earlier in development (like the scapula) tend to be less variable than those with later fusion (such as metapodials). Similarly, shaft measurements of long bones show greater variability than articular measurements.

Coefficient of variation. Calculating Pearson's coefficient of variation (r) for each measurement can help identify those with unusually high variability, which may then be excluded from scaling analyses (Thomas et al. 2013; Wolfhagen 2020). Horncore measurements, for instance, typically show higher coefficients of variation (often between 10-30%) compared to most long bone measurements (Albarella 2002).

Standard selection. The choice of standard reference is critical. Options include using individual modern specimens of known sex and age (Uerpmann 1979), calculating means from modern populations (Davis 1996; Payne and Bull 1988), or using archaeological assemblages as standards (Albarella and Payne 2005; Ducos 1968). Each approach has advantages and limitations, with archaeological standards

potentially offering better comparability to the material under study (Wolfhagen 2020).

2.2.3 The Log-Ratio Method

The log-ratio method has emerged as a particularly significant technique for zooarchaeological biometry, allowing researchers to combine measurements from different skeletal elements into a single analysis, thereby increasing sample sizes and statistical power. This technique, pioneered by Simpson (1941) and further developed by Meadow (1999), involves calculating the logarithm of the ratio between an archaeological measurement and the corresponding value from a standard reference specimen:

$$log\text{-}ratio = log_{10}\ (archaeological\ specimen/standard\ measurement)$$

This produces a series of dimensionless values that can be directly compared and analyzed collectively regardless of the specific element or measurement involved. A log-ratio value of zero indicates that the archaeological measurement is equal to the reference standard. Positive log-ratio values denote archaeological measurements that are larger than the reference, while negative values signify that the archaeological specimen is smaller than the reference standard.

The choice of reference standard is critical in this approach, with researchers typically selecting well-documented modern populations or well-preserved

archaeological specimens that provide comprehensive measurement sets (Wolfhagen 2020; Zeder 2024). For North Atlantic assemblages, the use of primitive breeds like Soay sheep as reference standards has proven particularly valuable given their morphological similarities to medieval livestock (Clutton-Brock et al. 1990; Noddle 1974, 1978). The Soay breed's status as a primitive northern short-tailed morphotype with potential morphological similarities to medieval Icelandic sheep makes it as appropriate a reference standard as possible for this current study (Adalsteinsson 1990; Pozo et al. 2023; Ryder 1983).

One particularly valuable extension of log-ratio analysis involves examining length and width dimensions separately, allowing researchers to differentiate between allometric changes (where proportions change with size) and isometric changes (where proportions remain constant despite size changes). This approach has proven especially useful for distinguishing between environmental influences (which often affect breadth more than length) and genetic changes (which typically affect all dimensions proportionally) (Wright and Viner-Daniels 2015; Zeder and Lemoine 2020).

2.3 Beyond Size: The Importance of Shape Analysis

Shape analysis in zooarchaeology encompasses several methodological approaches that move beyond simple size measurements to examine proportional relationships between different dimensions (Elewa 2004; Lele and Richtsmeier 2001). These approaches can reveal patterns related to species identification, sexual

dimorphism, and breed or regional variations that might not be apparent from size measurements alone (Gruwier et al. 2023; Telldahl 2012).

The log-ratio technique provides a particularly powerful tool for detecting shape differences between populations (Meadow 1981; Payne and Bull 1988). This approach allows researchers to determine whether archaeological populations differ merely in size or also in shape. If the mean ratio between each measurement and the standard remains constant across different measurements, the archaeological population likely shares a similar shape with the standard, merely scaled differently. Fluctuations in this ratio for specific measurements suggest morphological differences beyond simple scaling (Kazantzis and Albarella 2016).

Bivariate plots are another methodological approach central to shape analysis. By plotting pairs of measurements or calculating indices that express one dimension as a percentage of another, researchers can identify distinctive morphological patterns related to species, sex, or breed (Albarella 1997a; Davis et al. 2012). These approaches have proven particularly valuable for distinguishing between closely related species (e.g., sheep and goat) and for identifying sex-based differences in assemblages (Groot and Albarella 2022; Karaavci et al. 2024; Payne 1969).

The application of multivariate statistical methods, such as principal component analysis and discriminant function analysis, has further enhanced the analytical power of shape analysis in zooarchaeology (Morrison and Whitridge 1997; Popkin et al. 2012). These techniques allow zooarchaeologists to examine complex patterns of variation across multiple dimensions simultaneously, potentially illustrating subtle morphological distinctions that might be obscured in simpler

analytical approaches (Cussans 2010; Sykes et al. 2013). The theoretical significance of shape analysis lies in its ability to provide insights into both biological processes and cultural practices. Changes in animal proportions through time may reflect genetic selection for particular traits, environmental adaptation, or shifts in management practices (Bormetti and Albarella 2024).

2.4 Factors Affecting Morphology: A Theoretical Overview

Understanding the various factors that influence skeletal morphology is essential for interpreting biometrical data from archaeological assemblages. These factors can be broadly categorized as intrinsic (relating to the animal's inherent biological characteristics) and extrinsic (relating to external environmental and management conditions). The complex interplay between these factors creates the morphological patterns observed in the archaeological record. See Chapter 3: Biological and Environmental Factors Shaping Domestic Mammal Morphology for a complete discussion.

2.4.1 Intrinsic Factors: Biological Determinants of Morphology

Inherent biological attributes constitute the foundational elements that configure skeletal morphology in domestic mammals. These encompass genetically prescribed characteristics that govern developmental trajectories, sexual maturation processes, and comprehensive phenotypic manifestation (Frantz et al. 2020; McHugo et al. 2019; Zeder 2006). Understanding these intrinsic elements allows

zooarchaeologists to interpret morphological variation in archaeofaunal assemblages, distinguishing between genetic influences and environmental conditions or management practices (Clutton-Brock 1992).

Sexual Dimorphism emerges as one of the most consequential intrinsic elements affecting skeletal formation (Albarella 2002, 2017; Davis 2000; Greenfield 2006; Howard 1963; Weinstock 2006). Within mammalian taxa, male specimens typically exhibit larger and more robust skeletal architecture compared to females, although the magnitude of this dimorphism varies significantly across species and specific skeletal elements (Stearns 1977). This differentiation adheres to predictable patterns; notably, "Rensch's rule" illustrates how dimorphism increases allometrically with body size, with larger species generally exhibiting more pronounced sexual size differentials (Fairbairn 1997; Lindenfors et al. 2007). Osteometric data typically reveals more substantial sexual dimorphism in breadth (width) measurements than in length dimensions, reflecting the biomechanical necessities associated with supporting the increased muscle mass characteristic of male specimens (Bartosiewicz 1984; Meadow 1999; West 1990).

Breed Characteristics and Genetic Factors constitute another essential intrinsic determinant of morphological expression (Darwin 1868; Hall 1993; MacKinnon 2010; Orlando 2015) Domesticated species demonstrate remarkably greater phenotypic variability between breeds compared to their wild progenitors (Hall 2004; Zeder 2015). This variability becomes apparent through multiple quantifiable skeletal traits, including proportional relationships between elements, robusticity indices, and dimensional correlations. Genetic isolation – whether

resulting from geographic barriers or human-imposed breeding restrictions – facilitates the establishment of distinctive breeds with consistent skeletal attributes (Kantanen et al. 2000).

2.4.2 Extrinsic Factors: Environmental and Management Influences

While intrinsic factors provide the genetic foundation for skeletal development, external environmental conditions significantly modify how these genetic potentials are expressed phenotypically. Extrinsic factors – including geography, climate, nutrition, and human management practices – can profoundly reshape skeletal morphology, often producing changes that mimic or mask genetic differences.

Biogeographical Influences create distinctive patterns of morphological development based on environmental conditions. Several biogeographical principles help explain these patterns: "Allen's rule" describes how animals in colder environments typically develop shorter extremities than their counterparts in warmer regions, reducing surface area to minimize heat loss (Allen 1877, in Millien et al. 2006). "Bergmann's rule" suggests that populations in colder environments typically develop larger body sizes than those in warmer regions (Bergmann 1848, in Millien et al. 2006). "Guthrie's" or "Geist's rule" proposes that body size depends not primarily on temperature but on nutritional availability, specifically the duration of the "annual productivity pulse" (Geist 1987; Guthrie 1984). And island dwarfism describes how large mammals isolated on islands frequently undergo size reduction over time in response to resource limitations (Marshall and Corruccini 1978).

Nutritional Factors have been consistently identified as fundamental controllers of skeletal development. Animals require optimal nutritional conditions to achieve their complete genetic growth potential (Pálsson and Vergés 1952a), a circumstance rarely realized in challenging environments like the North Atlantic region. Nutritional status affects different skeletal elements and dimensions differently: later-developing elements typically show greater impairment under poor nutrition than early-developing ones, and breadth dimensions are generally more affected than length dimensions (Allen and Lamming 1961; Dickerson and McCance 1961). These differential effects create distinctive patterns that can be identified in archaeofaunal assemblages.

Human Management Practices like castration and shelter provision represent direct anthropogenic interventions that significantly affect morphology (Albarella 1999; Davis and Beckett 1999). Castration produces characteristic effects on bone development, particularly delayed epiphyseal fusion resulting in longer but more slender bones compared to intact males (Adcock 2022; Chahoud et al. 2023; Davis 2000). Shelter provision affects morphology primarily through energy conservation, reducing the diversion of resources from growth to thermogenesis in challenging environments (McArthur 1991; Smith 1964).

2.4.3 Theoretical Considerations in Factor Interaction

In practice, intrinsic and extrinsic factors rarely operate in isolation but interact in complex ways that can be challenging to disentangle in archaeological

contexts. Several key theoretical considerations must inform the interpretation of these interactions:

Differential Expression. The effects of both intrinsic and extrinsic factors are expressed differently across skeletal elements and dimensions. Some elements and measurements are more sensitive to certain factors than others, creating complex patterns of variation (Wright and Viner-Daniels 2015).

Temporal Dynamics. The timing of environmental stressors relative to developmental windows can significantly influence their morphological impact. Nutritional stress during critical growth periods affects different skeletal elements depending on their development schedule (Pálsson and Vergés 1952a, b).

Cumulative Effects. The morphological patterns observed in archaeological assemblages typically reflect cumulative effects of multiple factors operating across generations, rather than simple responses to single variables.

Taphonomic Considerations. Preservation biases can significantly affect the representation of different skeletal elements and morphological types in archaeological assemblages, potentially distorting interpretations of biological patterns (Maltby 1985).

2.5 Applications of Biometry to Archaeological Questions

Biometrical analysis extends far beyond simple morphological reconstruction to address major zooarchaeological questions regarding specialized production strategies, trade networks, social status, and economic transitions.

2.5.1 Economic Transitions and Productive Specialization

Biometrical analysis can address research questions on economic transitions and productive specialization in past societies. Albarella (1997b) examined zooarchaeological data from late medieval sites in England, including Launceston Castle, West Cotton, and Castle Mall (Norwich), documenting size increases in animals over time associated with distinct changes in mortality profiles. This combination of biometrical and demographic evidence indicated an economic shift from secondary product focus (milk and wool) toward increased emphasis on meat production, with corresponding improvements in animal conformation.

Davis (2008) identified a similar pattern in Portugal, finding evidence for sheep size increases during the Islamic period, particularly in breadth measurements. This change was interpreted as reflecting the cultural preference for mutton and resulting shift from wool to meat production. The fact that cattle showed no corresponding change during this period, but increased in size during the subsequent Christian era, further highlight the cultural specificity of these economic shifts.

The metrical identification of castrates (wethers in sheep; steers in cattle) provides particularly valuable insights into specialized production strategies. At the Anglo-Saxon site of Flixborough, England, Dobney and colleagues (2007) found evidence for a significant increase in oxen in one phase, indicated by distinctive metacarpal measurements and corresponding with a high proportion of elderly cattle. This pattern was interpreted as reflecting increased emphasis on draught animals during this period - a valuable commodity in Anglo-Saxon England (Cussans 2010).

In the Icelandic context, biometrical analysis has revealed significant transitions in livestock management strategies over time. The progressive shift from cattle-dominated to sheep-dominated economies between the *Landnám* (or Settlement) period and medieval era is reflected in changing biometrical profiles of livestock remains. As McGovern and colleagues (2007) have demonstrated, the earlier *Landnám* assemblages show evidence for more diverse animal management strategies, with cattle remains exhibiting greater dimensional variability than in later periods. By the medieval period, sheep measurements show greater standardization, potentially reflecting more specialized wool production strategies as Iceland became increasingly integrated into European trade networks through the export of *vaðmál* (homespun woolen cloth) (Cesario 2021).

These examples demonstrate how biometrical evidence, particularly when combined with mortality profiles can reveal transitions in economic focus within and across archaeological sites and productive specialization.

2.5.2 Trade, Exchange, and Cultural Contact

Biometrical studies offer valuable perspectives on trade networks and cultural contact in archaeological contexts. The analysis of faunal morphology can reveal patterns of livestock movement, breeding stock exchange, and the introduction of new animal varieties through trade or cultural contact.

In the North Atlantic context, biometrical analysis has proven valuable for understanding connections between isolated settlements and broader European networks (Cussans 2010; Hambrecht 2012, 2015). At Gásir, a medieval trading site in

northern Iceland, Harrison (2009) documented unusually large cattle remains compared to contemporary rural settlements, potentially indicating the presence of imported breeding stock or specialized production for provisioning foreign merchants. The biometrical distinctiveness of these animals, coupled with evidence for exotic trade goods at the site, suggests Gásir functioned as an important node connecting Iceland to broader North Atlantic and European trade networks (see Chapter 5: Materials, Methods, and Comparative Sites for further discussion of Sveigakot, Hofstaðir, and Gásir).

Similarly, Cussans' (2010) comparative analysis of livestock measurements from various North Atlantic settlements revealed distinctive regional patterns that correspond with known historical connections. The sheep remains from Norse settlements in Greenland, for instance, exhibit biometrical affinities with Icelandic specimens, reflecting the historical narrative of Greenlandic settlement proceeding from Iceland (Cussans 2017). These biometrical patterns provide tangible evidence for the movement of livestock along with human populations during the Norse expansion across the North Atlantic and provide a basis for this current research. The identification of morphologically distinctive specimens that differ from local populations might indicate imported breeding stock, while patterns of morphological change over time could reveal shifts in cultural and economic connections with mainland Europe.

2.5.3 Status and Social Differentiation

Biometrical analysis can provide valuable insights into status differentiation and social hierarchies in past societies. The distribution of different animal morphotypes across settlement types often correlates with status distinctions, as higher-status sites typically show evidence for larger, better-managed livestock populations than contemporary lower-status sites.

In the North Atlantic context, McGovern and colleagues (2009) documented differences in sheep bone robustness between Hofstaðir (a high-status chieftain's farm) and Sveigakot (a marginal tenant farm) in Iceland. While the difference was attributed primarily to nutritional variation rather than genetic distinctions, it nevertheless reflects status-based differential access to resources, with the higher-status farm maintaining better-nourished livestock.

Hambrecht's (2011, 2012) analysis of the Skálholt assemblage identified evidence for distinctive cattle management practices, including the presence of both naturally and artificially polled specimens (Utsunomiya et al. 2017). The morphological distinction of these animals from typical Icelandic cattle of the period suggests specialized breeding practices and potentially connections to European agricultural improvement movements, reflecting the elevated status and continental connections of this ecclesiastical establishment – one of the core questions of this present research.

The biometrical signatures of status differentiation extend beyond simple size distinctions to include evidence for specialized production strategies, distinctive

breeds or types, and management practices that would have required substantial investment in infrastructure and knowledge. In the North Atlantic context, biometrical analysis offers particularly valuable perspectives on how status differentiation operated within societies practicing ostensibly similar subsistence strategies.

2.6 Methodological Challenges and Future Directions

Despite its analytical potential, biometry has continued to confront several methodological challenges that warrant careful attention to maximize its interpretive contribution to archaeological research more broadly.

2.6.1 Integration with Other Analytical Approaches

A persistent challenge in zooarchaeological biometry is the methodological divide between practitioners who emphasize biometrical approaches and those who prioritize other analytical methods. Albarella (2002:61) notes that this division reflects not theoretical differences but rather "idiosyncrasies of different researchers or schools of research." Integrating biometrical analysis with other zooarchaeological approaches – particularly taphonomic studies, mortality profiles, and spatial analysis – strengthens interpretations and provides more holistic understanding of past human-animal relationships.

Particularly promising integrative methodologies combine biometrical datasets with multiple complementary lines of evidence, including:

Age Profiles. The correlation of biometrical patterns with age-at-death data can reveal relationships between animal size and management strategies, particularly whether larger or smaller animals were preferentially culled at specific ages.

Pathologies. The relationships between morphological characteristics and pathological conditions allow for analysis of management and husbandry practices and activity patterns (McGovern et al. 2009).

Taphonomic Patterns. Taphonomic factors potentially affect the representation of different morphological types in assemblages.

These integrative approaches require collaboration between specialists with different methodological expertise, as well as research designs that incorporate multiple analytical techniques from the outset. As this current dissertation is only one component of the larger results from the Skálholt faunal assemblage, further integration of some of these other approaches will be published elsewhere.

2.6.2 Standardization and Comparability

The comparability of biometrical data across different studies remains a significant challenge. Variations in measurement standards, recording protocols, and analytical methods limit the potential for large-scale comparative research. While complete standardization may be neither possible nor desirable, greater methodological transparency and consistency in basic measurement techniques would enhance data comparability without stifling methodological innovation (Meadow 1999).

The statistical treatment of biometrical data has become increasingly sophisticated, with standard protocols now including normality testing through methods like the Shapiro-Wilk test (Shapiro and Wilk 1965) and assessment of variance homogeneity using Levene's test (Levene 1960). When assumptions of normality and homogeneity of variance are met, parametric tests like ANOVA can be employed, followed by post-hoc comparisons using techniques such as Tukey's Honest Significant Difference test (Fisher 1925; Tukey 1949). For datasets that violate these assumptions, non-parametric alternatives like the Kruskal-Wallis test (Kruskal and Wallis 1952) provide robust alternatives, often followed by pairwise Wilcoxon rank-sum tests (Wilcoxon 1992) or, for more nuanced comparisons between groups with unequal sample sizes, Dunn's test with Benjamini-Hochberg correction (Benjamini and Hochberg 1995; Dunn 1964) for multiple comparisons.

These statistical approaches represent significant advancements in the analytical rigor of zooarchaeological biometry. However, their effective application requires careful consideration of underlying statistical assumptions and appropriate contextualization of results. The increasing accessibility of statistical software packages has democratized access to these sophisticated techniques, though this accessibility must be accompanied by methodological understanding to prevent misapplication or overinterpretation (Evin et al. 2023; Pozo et al. 2023; Wolfhagen 2020).

In Iceland, challenges of standardization and comparability are particularly evident when attempting to integrate data from earlier excavations with contemporary research. The pioneering zooarchaeological work in Iceland conducted by researchers

like Amorosi (1996) employed measurement protocols that differ in some respects from current standards, creating challenges for direct comparison with more recent datasets.

2.6.3 Technological Advancements

Recent developments in advanced imaging technologies and sophisticated statistical methodologies present new opportunities for advancing biometrical analysis. The increasing availability of digital measurement tools, three-dimensional imaging technologies, and specialized statistical software applications has mitigated some traditional barriers to comprehensive biometrical studies (Gaastra 2023). These technological developments, combined with renewed appreciation for the interpretive value of metric data, suggest promising trajectories for future research.

The continued refinement of multivariate statistical methodologies offers to aid in addressing the complex interactions between diverse factors affecting animal morphology. Principal component analysis, discriminant function analysis, and other multivariate techniques facilitate identification of subtle patterns in biometrical data that might remain obscured in more simplistic analytical approaches (Grau-Sologestoa et al. 2021). These methodologies are especially valuable for distinguishing between different causal factors influencing morphology, such as differentiating genetic from environmental influences on skeletal development (Wolfhagen 2020).

Recent advances in geometric morphometrics (GMM) offer significant potential for capturing and analyzing morphological variation beyond traditional

linear measurements (e.g., Larson et al. 2007; Magee et al. 2014; Orlando 2015). This technique, which records the three-dimensional shape of skeletal elements through digital coordinate-based methods, allows for more nuanced analysis of shape variation than conventional biometrical approaches. While the application of geometric morphometrics in zooarchaeology remains in its relative infancy compared to its implementation in other archaeological domains such as lithic analysis, it offers substantial potential for addressing questions about the relationship between genetic heritage and bone shape in livestock populations (Owen et al. 2014; Gaastra 2023). Unlike traditional linear measurements, GMM enables comprehensive analysis of shape independent of size, allowing researchers to identify subtle conformational differences between morphologically similar specimens (Jeanjean et al. 2023).

The integration of biomolecular approaches with traditional biometry represents another promising direction for future research (Der Sarkissian et al. 2015; Frantz et al. 2020; Orlando and Cooper 2014). Ancient DNA (aDNA) analysis provides direct evidence of genetic relationships and ancestry, complementing morphological data derived from biometrical analysis (Nieto-Espinet et al. 2021; Shapiro and Hofreiter 2014). The technique of genotyping prehistoric populations through aDNA extraction has substantially expanded the range of research questions that can be addressed through faunal remains, allowing direct assessment of genetic factors underlying morphological variation (Özdoğan et al. 2024). When combined with traditional biometrical data, aDNA analysis enables more precise identification of the drivers of morphological change in past animal populations (Trentacoste et al. 2018).

Similarly, stable isotope analysis offers valuable insights into diet, mobility patterns, and environmental conditions that might have influenced morphological development (Cannon et al. 1999; Guiry 2012; Rick et al. 2011; West and France 2015). Techniques such as stable isotope geochemistry can reveal feeding patterns and degrees of livestock mobility that directly affect skeletal morphology. Additional approaches from biomolecular archaeology, including ZooMS (Zooarchaeology by Mass Spectrometry), enable species identification and characterization of protein preservation in fragmentary specimens that might be unsuitable for traditional biometrical analysis (Adcock 2022; Buckley et al. 2009; Collins et al. 2010).

2.7 Conclusion: Biometry as Interpretive Framework

Biometrical analysis in zooarchaeology has undergone substantial methodological refinement, transforming from a predominantly descriptive exercise into a sophisticated analytical approach capable of addressing complex archaeological questions. As this chapter has demonstrates, contemporary biometrical methods provide valuable insights into species identification, morphological variation, human-animal relationships, trade networks, and cultural practices – dimensions of past human activity that frequently remain inaccessible through other analytical approaches.

The methodological advances examined herein – particularly the development of scaling techniques and sophisticated approaches to shape analysis – have significantly expanded the interpretive potential of zooarchaeological biometry. When integrated with complementary analytical approaches and applied with

appropriate methodological rigor, biometry constitutes a powerful tool for understanding the multifaceted roles of animals in past societies and their entanglement within broader social, economic, and environmental systems.

The theoretical framework established in this chapter highlights the complex interplay between intrinsic and extrinsic factors affecting animal morphology. Understanding how genetic factors like sexual dimorphism and breed characteristics interact with environmental influences such as climate, nutrition, and human management practices is essential for interpreting biometrical patterns in archaeological assemblages. By applying this nuanced theoretical perspective to the analysis of faunal remains from Skálholt and comparative North Atlantic sites, this research develops a sophisticated understanding of livestock morphology and its relationship to broader patterns of cultural adaptation and economic change in these marginal environments.

As Albarella (2002) concluded, future advancements in zooarchaeological biometry depend on "producing good quality work, well integrated with the rest of the archaeological evidence," combined with increased recognition of biometrical analysis's importance and adequate research support. By addressing these methodological challenges, zooarchaeologists can continue to refine biometry as a vital component of archaeological investigation.

For the present analysis of livestock remains from Skálholt and comparative North Atlantic sites, this theoretical and methodological framework provides essential tools for interpreting biometrical patterns and situating them within broader contexts of environmental adaptation, cultural exchange, and economic development. Through

systematic examination of both the distinctive characteristics of the Skálholt assemblage and its comparative relationship to other sites, this research evaluates whether Skálholt's livestock management strategies reflect engagement with broader European patterns of agricultural improvement during the early modern period, or whether they represent more regionally-specific adaptations to Iceland's distinctive environmental and economic contexts.

Chapter 3: Biological and Environmental Factors Shaping Domestic Mammal Morphology

This chapter examines the diverse array of biological and environmental factors that influence domestic mammal morphology, providing essential theoretical foundations for interpreting the biometrical patterns observed in the Skálholt assemblage. Understanding these factors is crucial for distinguishing between genetic characteristics, environmental adaptations, and human management practices when analyzing archaeological faunal remains. As Albarella (2002) observed, "one of the problems with metric analysis is that many causal factors affect both size and shape," creating interpretive challenges that necessitate systematic approaches to disentangling these influences.

By categorizing morphological determinants as either intrinsic (relating to the animal's inherent biological characteristics) or extrinsic (relating to external environmental and management conditions), this chapter establishes a framework for analyzing the complex interactions that shape animal morphology in archaeological contexts. Intrinsic factors, including sexual dimorphism and breed characteristics, constitute the genetic foundation upon which external influences operate. Extrinsic factors, such as biogeographical conditions, nutritional status, and human management practices, modify how these genetic potentials are expressed phenotypically, often creating distinctive patterns that can be identified through biometrical analysis.

The chapter pays particular attention to how these factors manifest in North Atlantic contexts, where challenging environmental conditions, limited resource

availability, and geographical isolation created distinctive adaptive pressures on livestock populations. By examining how each factor influences skeletal development, and how these influences interact across different elements and dimensions, this discussion provides essential context for interpreting the morphological patterns observed in the Skálholt sheep and cattle assemblages. This theoretical foundation will inform subsequent analyses of how Skálholt's livestock management strategies reflected both adaptation to Iceland's distinctive environmental constraints and potential engagement with broader European agricultural innovations during the early modern period.

3.1 Intrinsic Factors Affecting Morphology

Intrinsic factors represent the inherent biological characteristics that shape skeletal morphology in domestic mammals. These include genetically determined traits that influence growth patterns, sexual development, and overall phenotypic expression (Frantz et al. 2020; McHugo et al. 2019; Zeder 2006). By understanding these intrinsic factors, zooarchaeologists can more accurately interpret morphological variation in archaeological assemblages, distinguishing genetic influences from environmental and management effects (Clutton-Brock 1992).

3.1.1 Sexual Dimorphism

Sexual dimorphism – the systematic difference in morphology between males and females – represents one of the most significant intrinsic factors influencing

skeletal development in domestic mammals. The study of sexual dimorphism provides critical insights for zooarchaeologists attempting to reconstruct herd demographics, management strategies, and economic practices from faunal remains (Albarella 2002, 2017; Davis 2000; Greenfield 2006; Howard 1963; Orton 2020; Weinstock 2006).

Evolutionary Mechanisms and Biological Foundations

Sexual dimorphism emerges through interacting evolutionary processes combining sexual and natural selection (Cassini 2023a, b). While ancestral mammals were largely monomorphic with minimal sexual selection pressure, subsequent ecological shifts and changing reproductive strategies drove the evolution of dimorphism across different lineages (Weckerly 1998). Notably, most sexually reproducing animal taxa exhibit female-biased size dimorphism (e.g., Arachnida, Cephalopoda, Crustacea, Annelida), primarily because females bear the physiological burden of carrying eggs or offspring (Fairbairn 1997; Lindenfors et al. 2007).

Mammals, however, predominantly exhibit male-biased size dimorphism. This evolutionary divergence stems from distinct reproductive strategies where mammalian females invest heavily in fewer offspring with extended postnatal care periods. For males, particularly in polygamous species, larger body size confers significant reproductive advantages in territorial competition (Stearns 1977). The capacity to secure and defend optimal feeding territories directly influences access to females and subsequent reproductive success (Capellini 2007). Traditional explanations for male-biased dimorphism emphasized sexual selection – males

competing for mates, with larger males siring more offspring. However, contemporary research reveals a more nuanced picture involving both sexual and natural selection processes (Isvaran and Sankaran 2017; van der Bijl 2018; Young and Bennett 2013). In many taxa, ecological pressures catalyzed evolutionary changes in body size that subsequently influenced dimorphism patterns. For instance, shifts from closed to open habitats increased predation risks for antelope populations, favoring larger body size initially, with sexual dimorphism emerging secondarily through differential selection pressures on males and females (Jarman 1974).

Morphological Patterns and Taxonomic Variation

The expression of sexual dimorphism across mammalian taxa follows several predictable patterns while exhibiting taxon-specific variations reflecting evolutionary history and ecological adaptations. Through evolutionary processes, certain mammalian groups – notably primates, ungulates, and marine carnivores – have diverged from ancestral traits to develop diurnal activity patterns, increased body size, complex social structures, pronounced sexual dimorphism, and elevated rates of polygynous mating systems, while many other lineages have maintained more primitive mammalian characteristics (Fairbairn 1997; Ralls 1977; Weckerly 1998).

In pinnipeds (seals), sexual size dimorphism evolved before changes in the mating system (Cassini 2023a). Environmental changes – particularly water temperature shifts leading to deeper diving behaviors – may have selected for larger males, enabling ecological niche partitioning between sexes (Krüger et al. 2014). Similarly, in primates, dimorphism evolved following increases in body size

associated with a shift from nocturnal to diurnal activity patterns and the consequent changes in predation pressure (Cassini 2023b; Shultz et al. 2011). Among artiodactyls – the order containing domestic ungulates central to zooarchaeological research – transitions from closed to open habitats triggered increased body size, gregariousness, and dietary specialization, with sexual dimorphism appearing primarily after niche separation between males and females (Jarman 1974).

While male mammals typically exceed females in size, this dimorphism manifests disproportionately across the body, with the disparity markedly greater in total body weight than in skeletal dimensions. This pattern is clearly illustrated in alpine ibex (*Capra ibex*), where females weigh only half as much as males, yet their skeletal elements maintain 80-85% of male bone weight (Fernández and Monchot 2007). This phenomenon is similarly documented in red deer (*Cervus elaphus*) populations (Mitchell and Grant 1981). Sexual dimorphism follows several predictable patterns across mammals. "Rensch's rule" demonstrates that dimorphism scales allometrically with body size – as species' average body mass increases, the degree of sexual size dimorphism intensifies proportionally (Fairbairn 1997; Lindenfors et al. 2007). This relationship has direct implications for zooarchaeological research, suggesting that cattle remains should exhibit more pronounced sexual differentiation than sheep, potentially enabling more precise demographic reconstructions of archaeological cattle assemblages (Cussans 2010).

Beyond absolute size differences, male mammals develop more robust skeletal structures to support their greater muscle mass. Consequently, bone measurements generally display more pronounced sexual dimorphism in breadth (or

width) dimensions than in length dimensions (Howard 1963). This differential expression of dimorphism across skeletal dimensions reflects both biomechanical requirements and varying selection pressures on different morphological aspects (Meadow 1999). The most reliable separation between sexes is typically achieved through examination of indices that combine dimensions taken across different planes rather than single measurements in isolation (West 1990). Developmental timing further influences the expression of sexual dimorphism. Bartosiewicz (1984) observed that later-fusing skeletal elements, having longer exposure to sex-specific hormonal influences during development, typically manifest greater sexual dimorphism – an observation with potentially significant implications for selective measurement protocols in zooarchaeological research. This developmental aspect highlights the importance of understanding both evolutionary and ontogenetic factors when interpreting skeletal remains.

The evolution of different reproductive tactics further complicates dimorphism patterns. Within species, males often employ divergent strategies: larger males typically monopolize females through direct contest competition, while smaller males develop alternative reproductive tactics (Trillmich and Trillmich 1984). These different mating strategies, maintained through equilibrium selection, create intra-sex variation that introduces additional complexity when interpreting skeletal measurements from archaeological assemblages. This complexity is further compounded in domestic species by the presence of castrates, whose skeletal measurements often overlap with both male and female ranges depending on the age at castration – a phenomenon examined in greater detail in Section 3.2.3.1.

Element-Specific Dimorphism in Domestic Mammals

Sexual dimorphism manifests with varying intensity across the skeletal structure of domestic ungulates, with certain elements providing more reliable indicators for sex determination than others. Understanding these element-specific patterns is essential for accurate demographic reconstruction from archaeological assemblages.

High-Dimorphism Diagnostic Elements

Pelvis

The pelvis represents one of the most sexually dimorphic skeletal elements due to its functional role in parturition (the birth of offspring). Beyond non-metric traits used to determine sex (particularly well-documented in sheep), metric approaches can provide reliable sex differentiation (Boessneck 1969; Hatting 1995). While male Soay pelves are larger overall, female pelves are relatively broader (Clutton-Brock et al. 1990). The ilium lengths of the Soay individuals were similar between sexes, contradicting Boessneck's (1969) finding of longer female ilia. Medial acetabular wall height serves as a diagnostic feature, being higher in males than females of both cattle and sheep (Prummel and Frisch 1986). Greenfield's (2006) research found that acetabular measurements provided complete separation between sexes in some species and strong bimodal distribution in others. His cattle data showed complete separation despite a small sample size, while sheep samples demonstrated greater overlap, particularly in mixed assemblages with varied environmental backgrounds.

The pelvis provides particularly valuable diagnostic measurements in zooarchaeological assemblages where preservation permits, as West (1990) achieved excellent separation of males and females across species through plotting pubis measurements (breadth and length). At sites like Skálholt, however, complete pelves are relatively rare in the assemblage, limiting the application of these reliable sex indicators.

Horncores

Horncores exhibit considerable sexual dimorphism, though hornedness itself varies significantly between breeds. In Soay sheep, rams develop substantial horns while ewes possess either diminutive horns or none (Clutton-Brock et al. 1990). Similarly in cattle, Grigson (1982) observed that bulls typically develop longer and stouter horncores than cows. The challenge lies in distinguishing sex-based variation from breed differences in mixed archaeological assemblages. Sykes and Symmons (2007) addressed this by demonstrating that basal circumference and minimum basal diameter measurements provide complete separation between males and females in medium and long-horned cattle varieties, though short-horned types (outer curve < 195 mm) have been shown to confound clear differentiation (Thomas et al. 2013).

In the Skálholt assemblage, horncores are present but not abundant, with evidence for both naturally and artificially polled cattle as noted by Hambrecht (2011, 2012). The presence of polled specimens limits the utility of horncores for sex determination at this particular site, though they do provide important evidence for specialized breeding practices (Utsunomiya et al. 2017).

Metapodials

Metapodial sexual dimorphism follows consistent patterns across bovids and caprines (Davis et al. 2012; O'Connor 1982; Reitz and Ruff 1994; Rowley-Conwy 1998; Thomas et al. 2013). Males typically possess longer metacarpals and metatarsals than females, with proportionally greater breadth relative to length (Berteaux and Guintard 1995; Howard 1963). Metacarpals also generally display greater sexual dimorphism than metatarsals among both sheep and cattle (Higham 1969).

In Shetland sheep, Davis (2000) found that shaft diameter (SD) exhibited the greatest sexual dimorphism among metapodial measurements, with metacarpal SD in rams averaging 18% larger than in ewes, and metatarsal SD showing a 15% difference. Greatest length (GL) measurements showed more modest dimorphism at 8% and 6%. When examining mixed breed samples, O'Connor (1982) demonstrated that distal metacarpal breadth/depth ratios could determine sex with 85% accuracy. However, he emphasized that these indices perform optimally only when comparing animals raised under uniform environmental conditions – a prerequisite seldom guaranteed in archaeological contexts.

In cattle, Berteaux and Guintard (1995) identified distal breadth (Bd) as the most sexually dimorphic dimension in both metacarpals and metatarsals. Higham (1969) similarly documented pronounced sexual dimorphism in metacarpal distal width and noted that breadth measurements generally show greater dimorphism than length measurements. Howard (1963) found that bull metapodials are consistently broader relative to length than cow metapodials, and Grigson (1982) suggested that

metacarpal distal breadth measurements should produce bimodal distributions. Despite these patterns, considerable overlap exists between male and female measurement ranges (Telldahl et al. 2012).

Metapodials feature prominently in the Skálholt assemblage, with 19 metacarpal and 11 metatarsal length measurements available for sheep, along with substantial width measurements (21 and 16 respectively). For cattle, fewer complete specimens are available, but width measurements are still well-represented. In the comparative Icelandic sites, metapodials are similarly well-preserved, making them particularly valuable for sex determination analysis across the North Atlantic datasets.

Moderately Dimorphic Elements

Femur

Davis' (2000) study of Shetland sheep showed that the femur displays significant sexual dimorphism, with rams having mean GLC (greatest length from the caput) measurements 11% larger than ewes, and SD (smallest breadth of the diaphysis) measurements 12% larger. In the more extremely dimorphic alpine ibex, Fernández and Monchot (2007) documented female proximal femur breadth (Bp) at only 80% of male values, while distal breadth (Bd) showed slightly less dimorphism at 82.8%.

Archaeological studies have identified population-specific femoral characteristics that appear genetically determined rather than environmentally induced (Zeder and Lemoine 2020). Noddle (1978) noted distinctive positioning of

the femoral nutrient foramen in Skara Brae sheep compared to mainland British specimens, suggesting localized genetic adaptation.

Femurs are relatively uncommon in the Skálholt assemblage, with only three width measurements for sheep and 12 for cattle. This pattern of limited femur preservation is consistent across most North Atlantic zooarchaeological assemblages, including the comparative sites from Iceland and Greenland.

Tibia

The tibia demonstrates varying degrees of sexual dimorphism across species. Bartosiewicz (1985) documented generally shorter tibiae in cows compared to bulls while Davis' (2000) study of Shetland sheep found tibial length averaging 12% greater in rams than ewes, with SD (smallest shaft diameter) showing the highest dimorphism at 15% in fully fused specimens. The distal breadth (Bd) exhibited much less dimorphism at only 5-6%, making it particularly valuable for examining non-sex-related variation. Similarly, the shaft diameter of the alpine ibex has been shown to be more sexually dimorphic (female means 79.3% of male values), with epiphyseal breadths showing less differentiation (Fernández and Monchot 2007).

The tibia's unique combination of highly dimorphic measurements (length and SD) alongside less dimorphic features (Bd) makes it particularly valuable in zooarchaeological studies for distinguishing between genetic, nutritional, and environmental factors affecting bone development when controlling for sex-based variation.

Tibiae are exceptionally well-represented in the Skálholt assemblage, with 58 width measurements for sheep and 18 for cattle, making them one of the most numerically significant elements in the dataset. Their abundance reflects both their robust nature and preservation conditions at the site.

Humerus

Humeral sexual dimorphism varies substantially across species. In alpine ibex, the smallest breadth of the diaphysis (SD) shows pronounced dimorphism, with female means less than 80% of male values (Fernández and Monchot 2007). By contrast, the same measurement in Shetland sheep shows only that ewe SD values are 93% of mean humeral widths in rams (Davis 2000). Davis also found greater dimorphism in greatest length from caput (GLC), with rams exceeding ewes by 11% – ranking this among the more sexually diagnostic measurements included in his study. Discriminant analysis suggests that a combination of GLC, SD, and breadth of the trochlea (BT) are the best metrics for determining sex from the humerus (Popkin et al. 2012).

Like tibiae, humeri are abundant in the Skálholt assemblage, with 49 width measurements for sheep and 18 for cattle. Their prevalence in the dataset makes them particularly valuable for population-level analysis, though their moderate sexual dimorphism means they must be interpreted cautiously when used for sex determination.

Radius (and Ulna)

The radius exhibits variable dimorphism across species. Radial dimensions potentially reach 20% dimorphism in cattle proximal measurements (Riedel 1977, cited in Grigson 1982). In alpine ibex, shaft diameter (SD) and distal breadth (Bd) show pronounced dimorphism, with female means below 80% of male values (Fernández and Monchot 2007). Shetland sheep display 11% difference in greatest length (GL) and 17% in shaft diameter (SD) (Davis 2000). The proximal breadth of the radius can vary between archaeological sites, with overlapping ranges observed in assemblages from Cnip, Dun Vulan, Sollas, and Udal on the Western Isles of the Hebrides (Cussans 2010).

Radii are well-represented in the Skálholt assemblage, with 34 width measurements for sheep and 14 for cattle. While complete specimens providing length measurements are relatively rare (only five for sheep), the abundance of width measurements makes the radius an important element for population-level studies at the site.

Skull

The skull itself displays measurable sexual dimorphism across domestic mammals. Clutton-Brock and colleagues (1990) observed that Soay rams possess longer skulls than ewes. Cattle bulls exhibit relatively broader skulls with particularly dimorphic frontal breadth measurements, though Howard (1963) noted that female aurochs (*Bos primigenius*) measurements overlapped with those of modern bulls. Grigson (1982) found that skull base length shows minimal dimorphism in cattle,

while other cranial dimensions present more pronounced differences. The extremities of the facial region appear particularly affected by sexual differentiation, with castrates showing distinct patterns compared to intact males and females (Clutton-Brock et al. 1990; Davis 2000).

At Skálholt and most North Atlantic sites, complete skulls are relatively rare in the assemblage, limiting their utility for sex determination despite their known dimorphic characteristics.

Atlas and Axis

The anteriormost vertebrae (atlas and axis) exhibit pronounced dimorphism in bovids and caprines. Grigson (1982) noted larger elements in bulls than cows, while Boessneck (1969) documented thicker, more massive vertebrae in male caprines. Clutton-Brock and colleagues (1990) attributed the greater robusticity in Soay rams to the biomechanical demands of supporting heavier horn structures – suggesting this dimorphism would be less pronounced in hornless breeds than horned breeds (Cussans 2010). Given that most Icelandic cattle crania found in contexts from *Landnám* to the medieval period are horned rather than polled, sexual dimorphism may be more apparent in those specimens (Hambrecht 2012; McGovern et al. 2009).

While vertebrae are present in the Skálholt assemblage, they are not included in the metrical analysis due to challenges in standardizing measurements and the relatively limited research on their dimorphic characteristics.

Scapula

The scapula shows moderate to significant sexual dimorphism, though with considerable variation between species (Popkin et al. 2012). Riedel (1977, cited in Grigson 1982) suggested cattle scapular distal measurements might exhibit sexual dimorphism exceeding 20%, though Grigson expressed methodological reservations about this claim, particularly regarding the reliable identification of castrates within a faunal assemblage. In Shetland sheep, Davis (2000) documented more modest dimorphism, with ram mean measurements only 7-9% larger than those of ewes. The scapula's early fusion time – occurring at approximately six months of age before substantial body size differentiation develops between males and females in caprines – is a potential limit in its utility for constructing sex-specific profiles (Zeder and Lemoine 2020).

Scapulae are minimally represented in the Skálholt metrical dataset, reflecting both preservation issues and measurement standardization challenges.

Low-Dimorphism Elements

Astragalus and Calcaneus

Tarsal elements typically exhibit minimal sexual dimorphism compared to other skeletal elements (Grigson 1969; Higham 1969; Noddle 1979; Popovici et al. 2011). Davis' (2000) study of Shetland sheep found astragalus GL (greatest length) and Dl (lateral depth) differing by merely 2% between rams and ewes, with calcaneus GL and astragalus Bd (distal breadth) showing slightly more dimorphism at 5% and 7% respectively (Cussans 2010; Noddle 1979). For cattle, Higham (1969) similarly found astragali and calcanea providing some of the least sexually diagnostic

dimensions. Alpine ibex also follow this pattern, with astragalus lateral length (GLl) showing the least dimorphism in Fernández and Monchot's (2007) study, with female means reaching 90% of male values.

This low sexual dimorphism makes these elements particularly valuable for investigating non-sex-related factors affecting bone morphology. The combination of low sexual dimorphism, minimal effects from castration, sensitivity to environmental factors, and age independence makes the astragalus and calcaneus particularly valuable for zooarchaeological studies seeking to identify environmental changes, nutritional regimes, or different breeds/types within assemblages while minimizing confounding variables.

Astragali and calcanei are well-represented in the Skálholt assemblage, with 10 width measurements for sheep astragali and 22 length measurements for sheep calcanei. These elements are similarly well-preserved across the comparative North Atlantic sites, making them particularly valuable for cross-site comparisons where controlling for sexual dimorphism is important.

Mandibles and Teeth

Dental elements demonstrate remarkably limited sexual dimorphism compared to other skeletal structures (Albarella 2002; Payne and Bull 1988). Grigson (1982) found no sex-based differentiation in cattle maxillary tooth rows or individual teeth, and Clutton-Brock and colleagues (1990) concluded that isolated Soay sheep mandibles cannot be reliably sexed. This contrasts with wild ungulates like caribou (*Rangifer tarandus*), where mandibles show measurable sexual dimorphism,

primarily in dimensions associated with the diastema rather than the tooth row (Bergerud 1964; Miller 1974; Morrison and Whitridge 1997). This pattern appears absent in sheep, as the Soay data show comparable mandibular dimensions between sexes (Clutton-Brock et al. 1990).

The conservative nature of teeth morphology – being less plastic than bones – makes their dimensions less affected by sex, age, and environmental factors, potentially serving as more direct indicators of genetic change (see Albarella 2002; Davis and Beckett 1999; Grau-Sologestoa et al. 2021; Payne and Bull 1988; Zeder 2006). While tooth size shows minimal sexual dimorphism, tooth eruption timing may differ slightly between sexes, with eruption potentially advanced in males relative to females (Worley et al. 2016). However, sex does influence tooth wear patterns, with statistically significant variation emerging in older cohorts, though ram tooth wear appears less affected by nutritional status than other sex-linked characteristics (Worley et al. 2016).

While teeth are present in the Skálholt assemblage, they are not included in the biometrical dataset due to their limited sexual dimorphism. Their value lies primarily in age determination rather than sex identification and fall out of the scope of this current work.

Phalanges

Sexual dimorphism in phalanges presents analytical challenges but remains detectable when elements can be separated by position (fore/hind limb and medial/lateral digit). Higham (1969) separated Aberdeen Angus cattle first phalanges

by limb and found significant sexual dimorphism in breadth measurements but minimal differentiation in length dimensions, with fore phalanges displaying slightly greater dimorphism than hind phalanges. In a study of elk (*Alces alces*) phalanges, Iregren (1985) observed comparable patterns of sexual dimorphism across both first and second phalanges from fore and hind limbs. However, Iregren expressed significant reservations regarding the practical application of these findings in archaeological contexts (Cussans 2010). While male specimens consistently displayed higher mean values than females, she noted that some of the female values were larger than the male mean values and displayed a considerable overlap in the ranges of male and female measurements (Iregren 1985). This substantial overlap in measurement distributions creates significant challenges for accurate sex determination using phalanges in zooarchaeological material, especially when dealing with incomplete specimens or assemblages comprising mixed populations.

Phalanges are present in the Skálholt assemblage but are minimally represented in the metrical dataset due to their limited utility for sex determination and the challenges in separating them by position.

Methodological Challenges in Zooarchaeological Applications

The skeletal elements of domestic ungulates exhibit varying degrees of sexual dimorphism, ranging from complete separation of male and female measurements in some elements to modest average size differences in others (Cussans 2010). The most reliable sex determination often comes from multivariate approaches examining indices of measurements taken across different planes (Howard 1963; West 1990). As

discussed above, the most sexually diagnostic measurements include horncore basal dimensions, pelvic metrics (particularly pubis and acetabulum), long bone shaft diameters (especially metacarpals), and major limb bone lengths (tibia, femur, radius, humerus) (Davis 2000). However, significant variation exists in the utility of different skeletal elements for sex determination – astragali and calcanea typically show minimal sexual dimorphism, while metapodials demonstrate more pronounced differences in both length and breadth (width) dimensions (Davis 2000; Higham 1969).

Despite established patterns of sexual dimorphism, several interconnected challenges complicate sex determination in archaeological assemblages. First, domestic sheep, cattle, and goats exhibit less pronounced sexual dimorphism than wild ungulates like alpine ibex (Fernández and Monchot 2007). While male means typically exceed female means across measurements, considerable range overlap often prevents confident sex assignment of individual specimens (Cussans 2010). This fundamental challenge is compounded by several additional factors, most notably the presence of castrates and mixed populations.

Castrates represent a significant proportion of domestic livestock populations, offering advantages in meat and wool production, traction capabilities, and management through reduced aggression (Albarella 1997b; Sherratt 1981). Their skeletal measurements typically overlap with both male and female ranges with the degree of overlap largely dependent on castration age (Davis 2000; Howard 1963). As detailed in Section 3.2.3.1, castration primarily affects bone development by delaying epiphyseal fusion, resulting in relatively longer bones compared to intact

males (Hatting 1983; Popkin et al. 2012). This delayed fusion particularly affects the limb bones, causing castrates to develop distinctively elongated femora, tibiae, and metapodials. Importantly, castration affects different elements and dimensions differentially, with bone length generally more affected than breadth measurements (Popovici et al. 2011). This creates distinctive morphological patterns where, for instance, ewes develop short and slender bones, rams develop tall and broad bones, and castrates (wethers and oxen) develop tall but slender bones, further complicating metric distinction between the three groups (Davis 2000).

The pelvis, which offers clear sex differentiation between males and females through both metric and non-metric traits, unfortunately provides limited insight regarding castrates, as the pelvic morphology of castrated males often resembles that of intact males if castration occurred after puberty. By contrast, horncores can demonstrate distinctive morphological changes in castrates, with smoothed surfaces and reduced dimensions, offering potential identification markers when these elements are preserved (Hatting 1975, 1983).

Mixed population samples – comprising animals from differing environmental backgrounds or different breeds – present another significant challenge, particularly at urban sites or trading centers where animals might arrive from various hinterland sources (Harrison 2009; O'Connor 2003). While sex determination may be relatively straightforward in homogeneous populations, mixed assemblages typically show increased measurement overlap between sexes, and archaeological contexts rarely permit confident assertions about population homogeneity. This challenge applies to virtually all skeletal elements but is most pronounced in elements with moderate

sexual dimorphism like the humerus and radius, where environmental factors can significantly influence dimensions that are already subject to sex-based variation.

Even when male and female measurements show complete separation without overlap, establishing the appropriate dividing threshold remains problematic. Sykes and Symmons (2007) observed that despite clear separation between female and male (including castrate) horncore measurements, experienced zooarchaeologists struggled to identify the correct division point. This difficulty highlights the inherent subjectivity in boundary determination even under ideal conditions of measurement separation.

The challenge of sex determination is further complicated by differential preservation patterns. Elements with high sexual dimorphism, like complete pelves, are often poorly represented in archaeological assemblages due to their fragility and lower bone density. In the Skálholt assemblage, for example, highly dimorphic elements like the femur (n = 3 for sheep) are drastically underrepresented compared to more robust but less dimorphic elements like tibiae (n = 58) and humeri (n = 49). This preservation bias can skew population reconstructions by limiting access to the most diagnostic elements for sex determination.

In sexually dimorphic populations, log-ratio distributions may exhibit bimodality, potentially revealing sex-based size clusters (Davis 2000; Albarella 2002). However, interpreting these distributions requires caution, as bimodality can also result from factors unrelated to sex, such as the presence of different species, breeds, age groups, or mixed wild and domestic populations (Albarella 2002; Payne and Bull 1988). This is particularly true for elements like the astragalus and

calcaneus, which exhibit limited sexual dimorphism but significant environmental plasticity.

For practicing zooarchaeologists, these challenges necessitate a multifaceted approach to sex determination. When possible, combining observations across multiple skeletal elements provides the most reliable results: high-dimorphism elements like the pelvis and horncores can establish clear male-female distinctions, while metapodial indices can help identify the presence of castrates. Additionally, analyzing elements with lower sexual dimorphism (astragalus, calcaneus, teeth) can provide baseline data on overall population characteristics less influenced by sex, against which the distributions of more sexually dimorphic elements can be compared. In assemblages like Skálholt, where multiple element types are well-preserved, this integrated approach offers the best strategy for reconstructing herd demographics and management practices despite the inherent challenges of archaeological sex determination.

3.1.2 Breed Characteristics and Genetic Factors

Beyond sexual dimorphism, genetic factors related to breed characteristics represent another fundamental intrinsic determinant of domestic mammal morphology. In contemporary Britain and across Europe, breed traits arguably constitute the most significant determinants of animal physical structure, reflecting centuries of focused husbandry targeting specific products and adaptations (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013).

Defining and Developing Livestock Breeds

The 'breed' concept in domestic animals combines biological and cultural classifications that have evolved over time (Zeder 2015). Breeds require consistent heritable traits, genetic isolation (through geographic or reproductive barriers), and phenotypic features reflecting human preferences rather than optimal survival adaptations (Clutton-Brock 1992; Darwin 1868; Hall 2004). Both natural and artificial selection contribute to breed formation, with their relative importance varying by economic purpose and environmental context (Hall 1993).

Domestic species exhibit remarkably greater phenotypic variation between breeds compared to their wild ancestors, a distinction that manifests clearly in skeletal morphology relevant to zooarchaeological analysis. This variation appears in multiple measurable skeletal traits including bone proportions, robusticity indices, and element size relationships. Hall (1993) identifies several mechanisms driving this skeletal diversity: activation of previously dormant genetic sequences through inbreeding, novel environmental stressors triggering new expressions, and genetic mutations from anthropogenic factors. These processes produce osteologically identifiable traits that, when beneficial, become selected either naturally or artificially over generations. The skeletal signatures of such selection appear most prominently in element proportions and specific growth patterns. Genetic isolation – whether through geographic separation or human-imposed breeding restrictions – remains the critical factor enabling breed establishment and the subsequent fixation of distinctive skeletal traits, particularly significant in island settings like Iceland after initial livestock introduction (Hall 2004). While geographic isolation predominated in the North

Atlantic region, creating distinctive island morphotypes recognizable in the zooarchaeological record, Hall (2004) notes that human cultural divisions based on ethnicity, language, or economic status can also create reproductive isolation within shared geographic areas, potentially resulting in the development of locally distinctive livestock varieties identifiable through biometric analysis.

Modern sheep breeds generally fall into four main categories: meat, wool, milk, and mixed/primitive/unimproved types (Guintard and Lallemand 2003). These categories reflect different selective pressures shaping their development, with each exhibiting distinctive morphological traits aligned with their primary economic purpose. Commercially valuable breeds developed for meat, milk, or wool typically reflect greater artificial selection pressure as breeders prioritize specific production characteristics (cf. Manning et al. 2015; Zeder 2006). Conversely, natural selection tends to exert greater influence on animals adapted to specific environmental challenges rather than commercial exploitation (cf. Cussans 2010; Davis 1981).

The North Ronaldsay sheep of the Orkney Islands exemplifies natural selection's influence on breed development. These sheep subsist almost entirely on seaweed – a diet extremely low in essential copper – and are confined to the foreshore (Tribe and Tribe 1950; Fenton 1997). As Cussans (2010) observes, cross-breeding experiments demonstrated that while hybrid offspring performed well on nearby islands with available pasture, none could "withstand the rigours and exposure of the North Ronaldshay [sic] coast" (Tribe and Tribe 1950), indicating natural selection for adaptations to harsh environmental conditions and low copper intake.

Wool-oriented breeds reflect selection for increased fiber productivity, quality, and fineness – with Fraser (1951) noting that pasture quality affects fiber characteristics, as poorer nutrition produces finer wool within the same breed. Dairy breeds prioritize milk production capacity. Meat production breeds demonstrate the most pronounced skeletal modifications, as their frames must support greater muscle and fat development.

Morphological Impacts of Breed Development and Improvement

The development of early maturation, particularly in meat breeds, represents one of the most significant transformations in domesticated livestock with clear osteological signatures. Hammond's (1932, in Cussans 2010) comparison of early-maturing Suffolk sheep with primitive Mouflon revealed distinct skeletal proportion differences: Suffolk lambs display body-depth to leg-length proportions resembling adult Mouflon ewes, providing archaeologically identifiable markers of developmental timing changes across skeletal regions.

These altered skeletal proportions stem from differential growth acceleration across the skeleton. In all mammals, skeletal development precedes musculature, which in turn precedes fat deposition, but in early-maturing breeds, these developmental stages become compressed and modified. Zooarchaeologically, this appears as a distinctive pattern: growth from skeletal extremities (head and feet, the earliest-developing elements) progresses inward toward the thoracic region through a "growth wave," with vertebrae ossifying last (Warmington and Kirton 1990). In early-maturing animals, this growth wave accelerates unevenly, producing diagnostic

skeletal signatures: notably shortened metapodials relative to upper limb bones, altered epiphyseal fusion sequences, and distinctive robusticity indices across skeletal elements.

The selective breeding of early-maturing meat animals produces identifiable osteological changes particularly relevant for zooarchaeological analysis. Archaeologically, this manifests as enhanced development of later-maturing elements – the pelvis, lumbar vertebrae, ribs, and upper limbs – while reducing dimensions of metapodials, cranial elements, and neck vertebrae through accelerated epiphyseal fusion (Hammond 1932, in Cussans 2010). This creates a diagnostic pattern: metapodial-to-upper limb bone ratios shift significantly, with metacarpals and metatarsals appearing relatively shorter compared to the humerus, radius, femur, and tibia than in unimproved breeds.

This dimensional redistribution creates measurable signatures where later-maturing skeletal elements appear proportionally larger in improved versus unimproved animals. A particularly diagnostic feature is increased bone thickness contributing to greater skeletal robusticity indices (Cussans 2010). Guintard and Lallemand (2003) demonstrated this pattern through metapodial morphometrics, with meat breed specimens consistently classified as “small” (short) yet “heavy” or “fat” in cross-section. Zooarchaeologically, this appears as distinctive breadth-to-length ratios that can be quantified through standard measurements and log-ratio analysis.

While these skeletal signatures often indicate selective breeding, similar morphological changes can also result from intensive feeding regimens. Hammond (1932, in Cussans 2010) noted that “thickness of bone and ultimate body size [i.e.,

muscle and fat weight] are both influenced by the same factor – body nutrition," creating an interpretive challenge for zooarchaeologists. This complex relationship between nutrition and breed characteristics requires careful analysis of multiple skeletal elements and dimensions to distinguish improved breeds from well-nourished unimproved animals in archaeological assemblages.

Selective breeding has produced additional osteologically identifiable modifications. Beyond direct size manipulation, breeding for reduced extremity size creates distinctive element proportion changes observable through metric analysis. An interesting counterpoint comes from Animal Breeding Research Organisation experiments where sheep selected for longer metapodials demonstrated significantly greater reproductive performance compared to control groups or short-cannon selections (Purser 1980) – a pattern potentially identifiable through demographic analysis of archaeological assemblages showing different metapodial proportions.

By the eighteenth century, selective breeding had successfully decoupled skeletal maturation from soft tissue development, enabling earlier slaughter than previously possible (Beckett 1990). Before this innovation, skeletal and soft tissue development remained more tightly linked, producing distinct age-at-death profiles potentially observable in archaeological assemblages. Breeding priorities shifted from simple size maximization toward specialized production traits including milk yields and meat-fat-bone balance (Pitchford 1993; Russell 1986; Trow-Smith 1959), each leaving distinctive signatures in skeletal morphology and slaughter patterns.

Historical Development of Livestock Breeds in Iceland and the North Atlantic

Understanding regional breed development requires examining initial domestication processes and subsequent livestock movement patterns has long been a foundational focus within zooarchaeology (Zeuner 1963). Sheep and goats were the first livestock species domesticated, once thought to have occurred around 10,000-9,500 BP (Clutton-Brock 1999; Ryder 1984; Zeder 2008). Initial domestication studies focused on morphological changes distinguishing wild from domestic animal bones (Uerpmann 1978; Rowley-Conwy 1995), with rapid size reduction upon domestication considered a key indicator (Clutton-Brock 1999).

Some researchers have questioned this automatic size reduction as a direct domestication response (Haber and Dayan 2004; Zeder 2015, 2024). Zeder (2008) argues that early deposits from hunting versus herding populations differ primarily in sex ratios rather than size – hunters typically targeted larger males, while early herders culled young males while maintaining female breeding stock. Detailed examination of age and sex profiles from Fertile Crescent sites identified early management strategies without morphological changes, pushing sheep and goat domestication dates back by approximately 1,000 years (Zeder 2008). Morphological changes associated with domestication, including size reduction and horn modification, occurred roughly 1,000 years after initial domestication, likely responding to new selective pressures when animals were moved to hotter, more arid environments and isolated from wild progenitors (Zeder 2006, 2008, 2024).

The spread of domestic mammals from the Near East across Europe into Britain and beyond formed part of the complex Mesolithic-Neolithic transition (see

Gron et al. 2020; Manning et al. 2013; Parmenter et al. 2015; Stanton et al. 2016). Some evidence favors a modified "demic diffusion" model – the migration of farming populations – with substantial indigenous hunter-gatherer contributions (Bentley et al. 2003). Bocquet-Appel et al. (2009) identified expansion pulses, contact zones, and barrier crossings before reaching "marginal zones" including Britain around 5000-4000 BC. Britain's adoption of the Neolithic package has been traced through radiocarbon-dated cereal grain analysis, showing limited cultivation between 3950-3800 cal. BC followed by substantial adoption between 3800-3000 cal. BC (Brown 2007). These cultivation dates correlate with megalithic tomb construction, suggesting rapid adoption once introduced (Schulting and Richards 2002).

Livestock introductions to more remote North Atlantic islands occurred much later, during the Norse expansion (Holm et al. 2014). When Scandinavian settlers colonized previously uninhabited landscapes such as Iceland and the Faroe Islands in the ninth century AD, they necessarily transported livestock with them (Dugmore et al. 2005, 2012; Grayson 2001; McGovern et al. 2007). This Norse colonization (*Landnám*) raises important questions about livestock origins: While the Icelandic cattle breed has been genetically isolated from other breeds for the past millennium, Holm and colleagues (2014) suggest Scandinavian settlers could have potentially spent time in the Shetlands or Hebrides before continuing to Iceland, potentially incorporating genetic contributions from outside Scandinavia.

Iceland's biodiversity changed dramatically at *Landnám* with the introduction of northwestern European livestock including cattle, pig (*Sus scrofa*), sheep, and goat (Dugmore et al. 2005). Though initial farming strategies derived from northwest

European practices and attempted to impose familiar agricultural patterns, environmental realities soon forced adaptations (Eddudóttir et al. 2020; McGovern et al. in press; Sveinbjarnardóttir 2018). By the eleventh and twelfth centuries AD, Icelandic farming strategies had shifted significantly, with pigs and goats virtually disappearing from the zooarchaeological record (Brown et al. 2012). Sheep-to-cattle ratios adjusted to better suit the increasingly deforested landscape, establishing the later medieval and early modern economy heavily dependent on sheep (Adalsteinsson 1990; Dugmore et al. 2012; Streeter 2011).

The modern Icelandic cattle breed has remained genetically isolated for over 1,000 years and likely shares close relationships with indigenous breeds from western Norway, particularly the Blacksided Troender and Nordland breeds (Kantanen et al. 2000; Holm et al. 2014). While small introductions of Danish breeds occurred in the nineteenth century, and potentially Jersey cattle at some point, genetic analyses using microsatellites and blood typing show minimal contributions from these later introductions (Brænd et al. 1962, in Holm et al. 2014). Though possible genetic influences from indigenous British breeds cannot be entirely ruled out given settlers' travel routes, such contributions appear not to have had significant genetic impact on Icelandic cattle populations.

Recent genetic research on the PLAG1 gene provides crucial insights connecting genetic markers directly to observable osteological characteristics in Icelandic cattle, including those from Skálholt. Studies examining ancient bovine DNA from northwestern Europe, including naturally polled crania from Iceland, found that both the Q allele of the PLAG1 region (associated with increased body

size) and the POLLED mutation have been present in Icelandic cattle for at least 1,000 years (Utsunomiya et al. 2017). This genetic evidence offers an interpretive framework for understanding the skeletal morphology observed in the Skálholt assemblage.

The genetic continuity is particularly significant: cattle remains from the early Settlement site of Hofstaðir contained the Q allele associated with increased body size, while a younger specimen from Skálholt also carried genetic signatures of this same growth-related allele. This suggests that the morphological differences observed in Skálholt cattle represent selective breeding practices rather than introduction of entirely new stock. Comparative analyses of cattle material from Gásir (fourteenth-fifteenth centuries AD) and Skálholt (seventeenth-eighteenth centuries AD) indicate approximately 1.2-fold size increases coinciding with rapid PLAG1 mutation proliferation affecting stature (Utsunomiya et al. 2017). In the Skálholt assemblage, this genetic pattern manifests as increased metapodial dimensions and altered proportional relationships between early- and late-maturing skeletal elements.

The POLLED mutation evidence is particularly relevant to Hambrecht's (2011, 2012) identification of naturally and artificially polled specimens at Skálholt. Rather than representing imported European stock, the genetic evidence suggests these polled animals reflect selection within the established Icelandic cattle population, where the genetic capacity for polledness had existed since the Settlement period. The skeletal manifestation of this trait—the absence of horn cores or their distinctive morphology in polled animals – provides an osteologically identifiable

marker of deliberate selection that reflects broader agricultural innovation strategies at Skálholt.

The genetic evidence also helps interpret the postcranial measurements from Skálholt's cattle. Unlike the English improvements of the "long" sixteenth century, which often involved dramatic size increases through new stock introductions (Thomas et al. 2013), the Icelandic pattern shows more modest dimensional changes achieved through selection within a genetically isolated population. This selection appears to have leveraged existing genetic variation, particularly the Q allele of PLAG1, to increase body size without fundamentally altering other breed characteristics adapted to Iceland's challenging environment. In the skeletal record, this manifests as altered proportions rather than wholesale size increases, with particular elements showing more pronounced changes than others.

This genetic and osteological evidence demonstrates that despite Iceland's geographic isolation, agricultural innovation at sites like Skálholt closely paralleled contemporaneous European "improvement" movements, albeit pursuing distinct strategies adapted to local conditions and working with a genetically constrained population. The PLAG1 evidence confirms that the skeletal changes observed at Skálholt represent deliberate selection rather than environmental fluctuations, allowing more confident interpretation of the metric patterns observed in the assemblage.

Unlike many modern breeds with rigid standardization, historical Icelandic livestock maintained considerable phenotypic diversity (Hambrecht 2011; Holm et al. 2014). Previously published faunal analyses suggest modest size increases in cattle

during the early modern period, though sample sizes from most Icelandic sites rarely permit comprehensive metric analysis (Hambrecht 2011, 2012). Holm and colleagues (2014) argue that existing zooarchaeological data suggesting that *Landnám* cattle were typically smaller than nineteenth-century specimens likely reflects their Norwegian ancestry.

This pattern parallels broader European agricultural developments, albeit following a distinctive trajectory shaped by Iceland's environmental constraints and isolation (Hambrecht and Gibbons 2017). While Iceland participated in the European agricultural improvement movement, as evidenced by Björn Halldórsson's 1780 agricultural manual *Atli* and other "improvement" journals from eighteenth-century farmers throughout Iceland, implementation necessarily adapted to local conditions (Halldórsson 1948, in Hambrecht 2011; Hicks 2019). Environmental evidence further supports this inclination for agricultural improvement, with a significant spike in barley pollen detected in seventeenth-century soil samples from Skálholt (Einarsson 1982), potentially indicating experimental barley cultivation at this ecclesiastical center.

Archaeological Evidence for Breed Characteristics

Archaeological evidence for livestock improvement appears through biometric analyses across numerous European and North Atlantic sites, illuminating the trajectories of change outlined in historical sources (Albarella 2002, 2017; Grau-Sologestoa et al. 2021; Thomas et al. 2013). Zooarchaeologists have developed methods to distinguish between different types of morphological change: skeletal

element enlargement without corresponding dental size changes suggests nutritional improvement, while dental modifications more likely indicate genetic changes through selective breeding or new stock introductions (Grau-Sologestoa and Albarella 2019; Thomas 2005). This distinction helps interpret archaeological data because teeth show less environmental plasticity than bones, potentially providing more reliable genetic change indicators.

The application of biometrical analysis to distinguish morphological variants or ancestral breed types in archaeofaunal assemblages has developed considerable methodological depth (Evin et al. 2023; Orton 2020). Noddle's (1974) metrical evaluation of ovine remains from Dun Mor Vaul, on Tiree, led to their characterization as resembling primitive northern short-tailed morphotypes, showing affinities with contemporary Scottish breeds like the Soay and North Ronaldsay. In her subsequent research, Noddle (1978) documented distinctive attributes in sheep remains from Skara Brae that departed from mainland British populations not only in dimensional proportions but also in anatomical features such as femoral nutrient foramen placement – indicating underlying genetic differentiation rather than merely phenotypic response to environmental conditions.

O'Connor (1988) examined York cattle horncore morphology through basal diameter and horn length measurements, identifying probable "Celtic Shorthorn" cattle during the Roman period. Metapodial measurements revealed larger cattle alongside native stock, with sheep remains similarly showing both small native and larger potentially introduced animals. Later medieval deposits from York showed horncore changes between Anglo-Scandinavian and later medieval periods without

corresponding post-cranial size changes, suggesting either genetic drift or supply source changes rather than overall body size modification (Bond and O'Connor 1999).

Albarella (2007) documented a key animal husbandry transition at the Iron Age-Roman transition in Britain: sudden mean cattle size increases accompanied by greater size variation, indicating small Iron Age-type cattle persisted alongside larger, likely continental imports. At Elms Farm, size increases appeared in teeth (lower third molar), astragali, and metatarsals, with no significant subsequent changes until the fifth century (Albarella et al. 2008). The dental size changes particularly suggested new stock introduction or genotype evolution rather than purely environmental improvements.

In Britain, the Second Agricultural Revolution (beginning in the late seventeenth century) marked a transformative period in livestock breeding, though significant "improvements" in animal husbandry were already underway from the late medieval period (Grau-Sologestoa and Albarella 2019; Thomas 2005). Archaeological evidence reveals size increases in cattle and sheep from the early fourteenth century in London, with the "long" sixteenth century representing a key turning point for innovation in animal husbandry that ultimately led to modern farming practices (Thomas et al. 2013). This suggests a more gradual and prolonged development rather than a sudden revolution (Davis 1997; Thomas 2005).

By the late sixteenth and seventeenth centuries, agricultural writers advocated for the selection of larger animals for breeding, initially emphasizing simple morphological characteristics, particularly size ("so bigge as bigge may be"), before

developing more sophisticated approaches (Skeat 1882, in Thomas et al. 2013). Documentary evidence shows an increasing understanding of heredity principles and more systematic breeding stock selection (Grau-Sologestoa and Albarella 2019). By the eighteenth century, breeding priorities shifted decisively from mere bulk size toward specific productive attributes including milk yields and meat-fat-bone proportions, aligning with an emerging "ethic of improvement" that valued both aesthetic and productive characteristics (Russell 1986; Trow-Smith 1959).

English sheep remains show statistically significant post-cranial measurement differences (width, length, depth) between Late Medieval, sixteenth century, and post-sixteenth century assemblages, demonstrating three-dimensional size increases beginning in the sixteenth century (Grau-Sologestoa and Albarella 2019). Late medieval assemblages from Launceston Castle, West Cotton, and Castle Mall (Norwich) demonstrate progressive animal size increases alongside changing sheep and cattle mortality profiles (Albarella 1997a). These combined indicators suggest economic reorientation from secondary product focus (milk, wool) toward meat production with deliberate conformation improvements.

Davis' (2008) biometrical analysis of sheep and cattle remains from archaeological sites across Portugal noted a significant pattern: during the Islamic period, sheep exhibited substantial size increases, with particular enlargement in breadth dimensions that surpassed the documented sexual dimorphism variation in modern Shetland sheep populations (Davis 2000). This morphological transformation was linked to Islamic cultural preferences for mutton consumption, catalyzing a production shift from wool toward meat emphasis, potentially facilitated through

genetic introductions from North African stock. The subsequent Christian period witnessed stable sheep dimensions while cattle underwent notable size increases, potentially reflecting dietary preference shifts or greater traction needs.

In the North Atlantic context, while genetic improvement may have proceeded more gradually than in Britain due to isolation and environmental constraints, evidence suggests that breeding strategies nonetheless evolved. By 1814, new sheep breeds including Northumberland muggs, Black-Face, and Cheviot were introduced to the Northern Isles to cross with native ewes, aimed at improving flock conformation (Cussans 2010). The principal regional breeds (Hebridean, Shetland, North Ronaldsay) demonstrate hardiness and fine bone structure that appears relatively stable from early archaeological examples.

These archaeological case studies demonstrate that biometric analysis, especially when combined with mortality profiles and historical documentation, can reveal subtle changes in livestock morphology resulting from selective breeding – whether for improved meat yields, traction capability, or adaptation to specific environmental conditions. The archaeological record thus complements historical accounts of breed development, providing empirical evidence for the timing and nature of morphological changes resulting from human selection.

3.2 Extrinsic Factors Affecting Morphology

While intrinsic factors provide the genetic foundation for skeletal development, external environmental conditions significantly modify how these genetic potentials are expressed phenotypically. Extrinsic factors – including

geography, climate, nutrition, and human management practices – can profoundly reshape skeletal morphology, often producing changes that mimic or mask genetic differences. This section examines how these external influences affect domestic mammal morphology, beginning with biogeographical principles that govern animal adaptation to different environments.

3.2.1 Biogeographical Influences

The relationship between animals and their geographic environments creates distinctive patterns of morphological development. For domestic mammals, variables such as altitude, latitude, temperature, and resource availability significantly shape skeletal growth patterns. Ecologists have established several key principles that help explain these biogeographical relationships, providing frameworks for interpreting morphological variation in archaeological assemblages.

Allen's Rule

Animals inhabiting colder environments typically develop shorter extremities than their counterparts in warmer regions – a pattern known as Allen's rule or the proportion rule (Allen 1877, in Millien et al. 2006). This adaptation efficiently reduces body surface area, thereby minimizing heat loss (Cussans 2017; Hugget 2004). Unlike other geographic effects that influence morphology primarily through nutrition, this principle represents a direct adaptive response to ambient temperature.

Experimental validation by Weaver and Ingram (1969) demonstrated this principle through raising littermate pigs at three different temperatures (5°C, 20°C,

and 35°C). Those raised in cold environments (5°C) developed notably stockier builds with shortened limbs and snouts compared to their siblings in warm conditions (35°C), yielding smaller surface-to-weight ratios. Pigs raised at median temperatures exhibited intermediate proportions, suggesting a graduated morphological response rather than a threshold effect.

While this experiment examined temperature extremes beyond typical regional archaeological studies, the observable differences even in the intermediate group indicate Allen's rule operates at more modest temperature variations. In archaeological contexts, this suggests livestock from colder regions should display shorter, more robust limbs compared to those from warmer areas, even within relatively constrained geographic boundaries (MacKinnon 2010). As climate conditions deteriorate and temperatures decrease, sheep limb length would correspondingly shorten to conserve body heat, potentially creating identifiable patterns across chronological sequences spanning climate fluctuations (Cussans 2010).

Bergmann's Rule

One of the most frequently cited biogeographical principles for explaining size variation in mammals, Bergmann's rule proposes that populations inhabiting colder environments typically develop larger body sizes than their counterparts in warmer regions (Bergmann 1848, in Millien et al. 2006; Davis 1981). This adaptation serves the same thermoregulatory function as Allen's rule – reducing the surface area

to volume ratio to minimize proportional heat loss in cold environments (Hugget 2004).

Researchers have repeatedly documented positive correlations between increasing latitude (and corresponding temperature decreases) and increased body size within mammalian species. Schrieder (1950) found that animals of the same or related species increased in size with increasing latitude and corresponding temperature decreases. Conversely, Davis (1981) observed that warming temperatures in the late Pleistocene Levant corresponded with size reductions across numerous mammal species. However, Lister (1997) suggests these size changes might reflect increased aridity rather than temperature directly, as drought conditions would substantially reduce available nutrition – potentially representing a more significant driver of size change than temperature alone.

Guthrie's or Geist's Rule

The dominance of temperature as the driver behind mammalian size variations has faced significant challenges from researchers examining broader geographical patterns. Geist's (1987) paper, provocatively titled "*Bergmann's rule is invalid*," highlighted that while many studies documented positive correlations between latitude and body size, others found contradictory patterns (McNab 1971). Examining deer and wolf populations across extensive latitudinal ranges, Geist (1987) discovered that body size increased with latitude only up to approximately 60-65°N, beyond which the trend reversed, with animals becoming progressively smaller at higher latitudes – a trend with particular relevance for the North Atlantic.

Geist (1987) proposed an alternative explanation: body size depends not on temperature but on nutritional availability, specifically the duration of the "annual productivity pulse" – the period of peak vegetation quality and quantity during growing seasons. At lower latitudes, arid conditions limit vegetation compared to temperate regions, while at higher latitudes, abbreviated summers and reduced solar angles similarly restrict growing seasons. Consequently, animals reach maximum size in temperate zones below 60°N where the annual productivity pulse reaches its peak, with size diminishing both northward and southward as nutritional resources become increasingly constrained. This theory has direct applications to North Atlantic settlements, where archaeological evidence from Norse Greenland shows smaller average bone sizes in the more northerly Western Settlement compared to the Eastern Settlement, supporting the hypotheses of decreasing bone size with increasing latitude – though multiple factors contribute to this pattern (Cussans 2017).

Similarly, Guthrie's (1984) examination of late Pleistocene-Holocene mammal size changes emphasized nutritional factors, arguing that changes in plant communities created less diverse resources with shorter growing seasons. This restriction of the somatic growth season represented, in Guthrie's assessment, the fundamental factor in late glacial dwarfing. Guthrie concluded that the growing season's quality and duration "better accounts for Bergmann's law than any other factor" (Guthrie 1984: 269). This principle helps explain the proposed sequence for skeletal changes in Norse Greenland, where sheep initially increased in size following settlement due to expanded grassland availability (temporarily increasing the "annual productivity pulse"), but subsequently decreased as climate deterioration reduced

pasture quality and quantity, preventing later animals from reaching the same dimensions as their predecessors (Cussans 2017).

Both researchers effectively reframed the latitude-size relationship, emphasizing that the critical factor is not temperature but nutrition – specifically the duration and quality of peak growth resources rich in usable protein necessary for skeletal development. This reinterpretation has significant implications for understanding livestock morphology across the North Atlantic, suggesting animal size responds more dramatically to pasture quality and seasonal duration than to ambient temperature directly. The 60-65°N turning point identified by Geist is particularly crucial for understanding latitudinal variations in Iceland and Greenland, as it suggests different body size trends should be expected in these regions compared to more southerly areas (see Cussans 2010). The observed patterns in Norse settlements appear to reflect these principles, with environmental conditions significantly affecting forage quality and growing season length, thereby influencing domestic mammal size in ways that align with Guthrie's and Geist's theoretical frameworks.

Island Dwarfism

The phenomenon of island dwarfism holds particular relevance for North Atlantic studies, as large mammals isolated on islands frequently undergo size reduction over time (Marshall and Corruccini 1978). This pattern appears across diverse species and locations, paralleling similar dwarfing processes observed in continental regions during the late Pleistocene (Shüle 1993).

Both island and continental dwarfing fundamentally reflect resource limitations (Guthrie 1984; Marshall and Corruccini 1978). Larger mammals maintain higher metabolic rates than smaller individuals of the same species, requiring greater energy intake (McNab 1990). When resources become restricted – whether through climate shifts, human competition, or the inherently constrained resources of island ecosystems – smaller body size confers adaptive advantages (Flannery and White 1991). Islands possess finite terrestrial resources that can support more small individuals than fewer large ones, thereby promoting selection for reduced dimensions (Frankham 1997, 1998). Additionally, genetic isolation necessitates maintaining population genetic diversity through higher numbers, further favoring smaller individuals (Bover and Alcover 2008; Dlugosch and Parker 2008). After isolation on islands, populations can decrease in size remarkably rapidly in response to resource constraints (Marshall and Corruccini 1978).

Island dwarfism progresses beyond simple ecophenotypic responses (growing less under resource constraints) to become genetically encoded. Based on studies of deer and elephant fossils, Lister (1996) identified two key stages in this process. Initially, resource shortages trigger ecophenotypic size reduction, which eventually extends beyond the normal size range through genetic adaptation. This genetic change can occur relatively quickly, over several thousand years (Sykes et al. 2013). Notably, purely ecophenotypic changes can manifest extremely rapidly – British red deer that decreased in size during the Holocene due to forest clearing returned to their original dimensions within 15-20 years after introduction to New Zealand's rich pastures (Lister 1997).

This phenomenon has particular significance for interpreting zooarchaeological assemblages from island settings across the North Atlantic. Evidence suggests that island dwarfism likely contributed to size differences between bones from smaller island groups (Orkney, Shetland, the Faroe Islands) and those from the larger landmass of Iceland. While Iceland's greater expanse provided substantially more potential grazing land compared to these smaller archipelagos, potentially moderating dwarfism effects, the phenomenon remains relevant when analyzing size variations across North Atlantic settlements (Cussans 2010). Similarly, Greenland's limited plant resources make island dwarfism an important consideration despite its considerable landmass. The principle that resource shortages drive dwarfing applies across these settings, though with varying intensity reflecting local conditions (Cussans 2017).

Within Iceland itself, additional factors beyond basic island constraints shaped livestock morphology. Differences in sheep bone robustness between the Icelandic sites of Hofstaðir and Sveigakot have been attributed to variations in nourishment rather than genetic divergence (Cussans 2010; McGovern et al. 2009). These intra-island variations highlight how local husbandry practices and environmental conditions interact with broader biogeographical principles.

McCormick (2007) noted a similar, though less extreme, phenomenon in Bronze Age Ireland; cattle from Dún Aonghasa on the Aran Islands were noticeably smaller than mainland Irish specimens. McCormick attributed this to environmental factors, suggesting the islands were less suitable for cattle rearing than mainland regions. This pattern was mirrored in pig remains, while sheep showed no significant

size difference between island and mainland sites, though mainland sample sizes were limited.

Seasonal Stress Patterns

Seasonal fluctuations represent another critical geographic factor affecting domestic mammal development, particularly in higher latitude regions with pronounced seasonal contrasts. The "annual productivity pulse" central to Guthrie's and Geist's rules fundamentally reflects seasonal patterns affected by latitude, precipitation patterns, and solar angle, which collectively determine vegetation growing season duration and quality (Geist 1987, Guthrie 1984).

In highly seasonal environments, especially at higher latitudes or in regions with distinct wet and dry periods, animals experience alternating phases of nutritional abundance and scarcity. These cyclical patterns can profoundly affect skeletal development, particularly when nutritional stress coincides with critical growth windows (Pálsson and Vergés 1952a). The specific timing of seasonal resource shortages can determine which skeletal elements and dimensions (length versus breadth) experience the greatest developmental impacts (Pálsson and Vergés 1952b).

Historical documentation indicates that seasonal management practices sometimes exacerbated these natural cycles, with animals occasionally maintained on summer pastures too long as seasons changed, creating additional nutritional stress during critical development periods (Brown et al. 2012; Thompson and Simpson 2007). Climatic deterioration likely led to a reduction in vegetation productivity and hence animal nutrition, impacting bone growth and potentially leading to smaller

livestock over time in Iceland specifically and across the North Atlantic (Simpson et al. 2001; Simpson et al. 2004). This could manifest in breadth measurements being preferentially diminished over length measurements due to poor nutrition. The direct effects of decreasing temperature (Allen's Rule – shorter limbs in colder climates) and the indirect effects of temperature on nutrition likely both played a role in influencing animal size and shape in response to climate change (Allen 1877, in Millien et al. 2006). The impact of seasonal variation becomes especially pronounced in marginal environments like island ecosystems or northern latitudes where growing seasons are severely compressed. In these contexts, livestock's resilience to seasonal resource fluctuations becomes a decisive factor affecting overall development and skeletal morphology.

Summary of Biogeographical Effects

While Allen's rule relates directly to temperature adaptation, most geographic effects on morphology operate primarily through nutritional pathways. On islands, available nutrition is constrained by the limited area available for plant growth. Across continental landmasses, nutrition is regulated by the "annual productivity pulse," which varies with precipitation patterns, solar angle, soil fertility, and other factors influenced by latitude, altitude, and geology.

These interconnected factors collectively determine nutrition quality and quantity available to domestic mammals. In regions where the "annual productivity pulse" is reduced through any mechanism, available nutrition and consequently individual body size typically diminish. Although research supporting Guthrie's and

Geist's rule derives primarily from studies of wild species, the principles likely apply to domestic mammals as well, though with additional complexity introduced by human management practices.

In zooarchaeological applications, biogeographical factors must be considered alongside other extrinsic influences (particularly direct nutritional management and shelter provision) and intrinsic factors (sex, breeding) when interpreting skeletal morphology. The complex interactions between these variables necessitate careful contextual analysis to identify the most probable causes for observed morphological variations in the archaeological record.

3.2.2 Nutritional Factors

Nutritional factors have been consistently identified throughout this chapter as fundamental controllers of skeletal development and ultimate morphological expression. Animals require optimal nutritional conditions to achieve their complete genetic growth potential (Pálsson and Vergés 1952a), a circumstance rarely realized in challenging environments like the North Atlantic region. While the biogeographical frameworks previously examined emphasize nutrition's foundational influence on animal form, nutritional dynamics extend beyond geographic determinism to encompass deliberate human manipulation of feeding regimes. This section investigates how nutritional parameters – both optimal and constrained – influence the skeletal configuration of domestic mammals.

Agricultural science has long prioritized understanding growth and productivity in livestock species, conducting extensive experimental research into

how nutritional limitations affect sheep and other domesticates. Particularly valuable for zooarchaeological applications is Pálsson and Vergés' (1952a, b) two-part investigation into the "effects of the plane of nutrition on growth and the development of carcass quality of lambs." Their findings, alongside subsequent research, establish critical principles connecting nutritional conditions to skeletal development patterns.

Nutrition and Overall Growth

Numerous controlled investigations have established that livestock provided with superior nutritional regimes achieve greater dimensional development. In contrast, animals subsisting on inadequate nutrition demonstrate retarded growth rates, delayed developmental timing, and fail to develop the characteristic proportions exhibited by their well-nourished counterparts (McCance et al. 1968; Pálsson and Vergés 1952a).

The research conducted by Pálsson and Vergés (1952a) revealed striking morphological divergence between animals maintained on differential nutritional planes when examined at identical chronological ages, with specimens from enhanced nutritional regimes exhibiting substantially larger carcass dimensions. Dickerson and McCance's (1961) comparative analysis of undernutrition in pigs evaluated undernourished subjects against either age-matched heavier specimens or weight-matched younger individuals. Similarly, Allen and Lamming (1961) documented how ewes receiving enriched nutrition not only achieved superior dimensional development but also reached reproductive maturity significantly earlier than their counterparts maintained on standard feeding protocols.

These nutritional influences transcend mere dimensional scaling to produce characteristic alterations in morphological proportions. Hammond (1952, in Cussans 2010) established that intensive feeding induces accelerated maturation patterns in domesticates that parallel changes achieved through selective breeding. Comparative analysis of specimens raised under varying nutritional conditions reveals distinct conformational differences, with well-nourished individuals developing notably more robust proportions compared to nutritionally restricted subjects.

Differential Effects of Poor Nutrition on the Skeleton

As established in earlier sections, developmental progression follows a directional wave pattern, initiating at peripheral elements and proceeding centrally toward the thoracic region (Warmington and Kirton 1990). This creates asynchronous skeletal maturation sequencing, with cranial elements and extremities developing precedence. Furthermore, skeletal elements achieve maturation earlier than soft tissue components, with muscle and fat developing subsequently.

Work by Dickerson and McCance (1961) indicated that nutritionally deprived pig specimens, when evaluated against weight-matched but chronologically younger well-nourished counterparts, exhibited disproportionately developed humeri. This finding demonstrates that under nutritional constraints, the organism prioritizes skeletal formation over alternative tissue systems. Consequently, in animals experiencing nutritional deficiencies, bone development maintains developmental precedence over muscular and fat tissue formation.

The skeletal system itself demonstrates internal hierarchical responses to nutritional restriction, with phylogenetically and developmentally conservative elements showing resistance to growth inhibition while later-maturing components exhibit heightened vulnerability. Pálsson and Vergés (1952a, b) established that cranial elements and distal appendicular components experienced significantly less developmental retardation than proximal limb elements, thoracic structures, and vertebral components. Lambs subjected to nutritional restriction displayed cranial and mandibular elements constituting significantly elevated proportions of total skeletal mass compared to control specimens. Conversely, developmentally delayed elements including scapulae and ribs represented diminished proportions of skeletal composition in nutritionally compromised specimens. McCance and colleagues (1968) documented parallel patterns in pigs, noting dental structures demonstrated marked resistance to nutritional insult compared with overall somatic development.

This prioritization pattern likely represents evolutionary adaptation ensuring preferential development of structures critical to immediate survival. Cranial elements provide essential neurological protection, while combined cranial and mandibular structures enable nutritional acquisition, and podial elements facilitate locomotion for resource procurement and predator avoidance. These functional imperatives create developmental buffering against nutritional deficit. Pálsson and Vergés (1952a) documented this selective allocation through late-gestational nutritional restriction experiments, which produced significant developmental impairment in podial elements during their peak growth phase, while cranial structures, despite simultaneous intensive development, demonstrated markedly reduced susceptibility to

growth inhibition – reflecting their heightened survival significance and consequent preferential resource allocation over appendicular extremities.

Bone Shaped by Poor Nutrition

Beyond its differential impact on various skeletal regions, nutritional status also distinctly affects bone development across different dimensions. Since longitudinal bone growth matures earlier than thickness development, nutritional deficiency impairs breadth expansion more severely than length increase; consequently, bone shape undergoes more substantial alteration than overall size (Pálsson and Vergés 1952a, b). Undernourished lambs develop noticeably more slender proportions than well-fed counterparts and comparative measurements of hindlimb bone length, minimum circumference, and weight per 10 cm revealed the least variation in length dimensions and the greatest in weight-to-length ratios, indicating that thickness development and possibly epiphyseal breadth experienced the most significant nutritional influence.

Research from the English Heritage "Sheep Project" reinforce these conclusions, demonstrating that nutritional enhancement generates disproportionately greater expansion in skeletal breadth dimensions relative to longitudinal growth (when comparing specimens raised on suboptimal pasturage versus those receiving high-quality grazing supplemented with additional feed). The expression of this phenomenon varies notably according to reproductive category (Popkin et al. 2012; Worley et al. 2016). All distal width measurements exhibited dimensional increases between nutritionally restricted and nutritionally optimized female specimens, with

male specimens displaying marginally more pronounced disparities between nutritional regimes. Notably, castrated individuals demonstrated a distinctive pattern where numerous distal breadth measurements showed negligible variation between nutritional planes, with dimensional increases primarily confined to astragalar, tibial, and humeral distal breadth (width) measurements.

These findings have significant implications for zooarchaeological interpretations. Increases in bone breadth without corresponding increases in length may indicate improved nutrition rather than genetic changes, while proportional changes in both dimensions might suggest genetic factors or combined genetic-nutritional influences. Understanding these differential effects can aid in separating the environmental signals from genetic ones when examining archaeological assemblages.

The Timing of Poor Nutrition

Our discussion of poor nutrition has thus far assumed a sustained condition – that animals experience nutritional deficiency throughout most of their lives. However, this assumption often proves inaccurate. Livestock frequently encounter nutritional shortfalls for relatively brief periods, such as during winters following poor harvests with limited fodder availability, or during particularly challenging weather conditions (see Section 3.3.3.2 on shelter provision).

Beyond studying animals maintained exclusively on either high or low nutritional planes, Pálsson and Vergés (1952b) also examined individuals whose nutritional status changed during development, raising some initially on high planes

followed by low planes (High-Low), and others on the reverse regime (Low-High). Given that different bones experience different growth intensities at different developmental stages, if nutritional deficiency coincides with a particular bone's peak growth period, that element will experience more significant developmental inhibition than others. For instance, late-maturing elements like lumbar vertebrae showed considerably greater growth retardation in the High-Low group than in the Low-High group. Conversely, the early-maturing jaw exhibited more severe growth impairment in the Low-High group compared to the High-Low group. Therefore, brief nutritional deficits may affect only certain anatomical regions, making their detection challenging without nearly complete skeletal remains for examination.

This timing effect has particular relevance for highly seasonal environments like Iceland, where winter fodder shortages could create annual periods of nutritional stress. Depending on animal age during these seasonal shortfalls, different skeletal elements might show varying degrees of developmental inhibition (Cussans 2010). Lambs born in spring would experience their first winter during a different developmental stage than those born later in the season, potentially creating cohort-specific patterns of skeletal development. Historical records indicate that fodder shortages were a recurring challenge in Iceland and other North Atlantic settlements, with periodic catastrophic losses during particularly harsh winters, events that would have selectively eliminated the most vulnerable animals and potentially shaped subsequent population morphology (Brown et al. 2012; Catlin and Bolender 2018; Dugmore et al. 2009).

Archaeological Evidence for Nutritional Effects

Zooarchaeological studies have documented numerous cases where nutritional factors appear to have influenced skeletal morphology. Arbuckle and Bowen (2004) examined cattle remains from colonial Chesapeake sites, identifying a size increase during the seventeenth century followed by a decrease in the early eighteenth century. These changes correlated with changing agricultural practices: during the seventeenth century, extensive tobacco farming created abundant fallow land where free-ranging cattle found plentiful forage, allowing size increases. When agricultural diversification in the eighteenth century reduced fallow acreage without changing the open-range husbandry system, cattle size diminished due to reduced nutrition.

In Iceland, evidence from multiple sites suggests nutritional factors influenced domestic animal morphology. McGovern et al. (2009) identified differences in sheep bone robustness between Hofstaðir and Sveigakot that appear attributable to nutritional variations rather than genetic differences. The more substantial sheep remains at Hofstaðir likely reflect better management practices and greater fodder availability at this higher-status farm compared to the more marginal Sveigakot settlement (Harrison 2009; McGovern et al. in press; Simpson et al. 2004).

Cussans (2017) documents size increases in Greenlandic caprine astragali between settlement phases dating from AD 1000 to 1300, with dimensions increasing approximately 8% – a change exceeding the 2% sexual dimorphism documented for this element (Davis 2000). This change likely reflects initial improvements in husbandry and pasture development following Norse colonization, temporarily enhancing the “annual productivity pulse” through landscape management. Later

decreases in bone size correlate with climatic deterioration and reduced vegetation productivity, highlighting nutrition's environmental dimension.

A key challenge for zooarchaeologists is distinguishing nutritional effects from genetic changes. Grau-Sologestoa and Albarella (2019) propose that skeletal element enlargement without corresponding dental size changes suggests nutritional improvement, while dental modifications are more likely to be indicative of genetic changes through selective breeding or new stock introductions (Thomas 2005). Teeth demonstrate less environmental plasticity than bones, potentially providing more reliable genetic indicators. This approach has helped identify cases where both genetic and nutritional improvements contributed to livestock development, such as in post-medieval England where increased bone size and subtle dental changes suggest both improved husbandry and selective breeding (Thomas et al. 2013).

Nutritional Challenges in the North Atlantic

The North Atlantic region presented particular nutritional challenges for domestic livestock. Iceland's volcanic landscape, with its limited soil development and vulnerability to erosion, offered restricted carrying capacity compared to more temperate European environments. The short growing season, especially at higher latitudes, limited the annual productivity pulse as described by Geist (1987) and Guthrie (1984). These constraints became more severe following initial deforestation during the settlement period, which reduced available biomass and accelerated soil erosion in many areas (Dugmore et al. 2005; McGovern et al. 2007).

Historical records document recurrent fodder shortages throughout Icelandic history, with farmers employing various strategies to maximize limited resources (Simpson et al. 2001). These included selective culling to reduce overwintering populations, utilization of marginal fodder sources such as seaweed and fish waste, and the development of intensive hay production systems to capture the brief summer productivity peak (Adalsteinsson 1990; Ogilvie 1984). The Greenlandic settlements faced even greater constraints, with a shorter growing season and more limited productive land, creating environmental conditions that would have significantly affected livestock development (Buckland et al. 1996; Cussans 2017; McGovern 1985).

Much of the archaeological evidence suggests that North Atlantic farmers adapted their husbandry practices to address these nutritional limitations (Thomson et al. 2005). Changes in culling patterns indicate increasingly careful herd management, with preferential retention of animals most adapted to local conditions (Hambrecht 2011; McGovern et al. 2007). The gradual shift from cattle-focused to sheep-dominated economies in both Iceland and Greenland reflects adaptation to nutritional realities, as sheep could more effectively utilize marginal grazing lands and required less winter fodder than cattle (McGovern et al. 2007, 2009).

Summary and Methodological Implications

The evidence presented clearly demonstrates nutrition's substantial influence on bone size and shape development. Insufficient nutrition reduces bone dimensions, though not to the same degree as overall body size reduction. It differentially affects

skeletal elements based on their maturation timing, with later-developing elements experiencing greater impairment. Bone breadth development suffers more than length growth, and the specific timing of nutritional deficiency periods most severely affects elements undergoing rapid growth during that interval.

Despite the valuable insights provided by studies like Pálsson and Vergés (1952a, b), several considerations must inform their application to archaeological material. While these studies sometimes employ linear measurements, they predominantly use bone weight as a size indicator. However, weight may not consistently correlate with external dimensions, as several factors beyond linear measurements affect bone mass.

Dickerson and McCance (1961) discovered that undernourished pigs developed thin, brittle cortical bone with enlarged marrow cavities resulting from medullary erosion. Similarly, Pratt and McCance (1964) found that animals subjected to prolonged severe malnutrition exhibited unusually thin yet dense cortical bone. Such structural changes might not alter external measurements but would significantly affect weight. Furthermore, Dickerson and McCance's (1961) findings revealed that undernourished animals' bones contained higher water percentages and lower proportions of fat, collagen, and calcium – potentially influencing bone mass. Additionally, nutritional stress in pregnant and lactating ewes triggers skeletal mineral resorption, reducing bone weight without affecting external dimensions (Benzie et al. 1955).

A final limitation worth noting is that most experimental studies do not examine fully mature animals (with complete epiphyseal fusion); Pálsson and Vergés

(1952a, b) studied animals only up to 41 weeks of age. Their research demonstrated that high/low plane growth differences were minimal at birth, maximal at nine weeks, and intermediate at 41 weeks – suggesting some compensatory growth occurred later in development. The extent to which this "catch-up" growth continues into full maturity remains uncertain, though complete compensation seems unlikely.

For zooarchaeologists, these findings have several important methodological implications. The differential effects of nutrition on different skeletal elements suggest that sampling strategies should include, when possible, both early and late-maturing elements when assessing nutritional status. The greater sensitivity of breadth (width) measurements to nutritional factors means that changes in bone shape (breadth-to-length ratios) may provide more reliable indicators of nutritional change than size alone. Comparison between teeth (less affected by nutrition) and postcranial elements (more responsive to nutritional changes) can help distinguish between genetic and environmental factors affecting morphology. And, age profiles must be carefully considered, as nutritional effects manifest differently across developmental stages and may appear less pronounced in fully mature specimens.

3.2.3 Human Management Practices

In addition to the environmental and nutritional factors discussed previously, direct human intervention through specific management practices significantly affects domestic animal morphology (Albarella 1999; Davis and Beckett 1999). These anthropogenic influences represent distinct extrinsic factors that can produce dramatic changes in skeletal development, sometimes mimicking, masking, or interacting with

both intrinsic genetic factors and other extrinsic environmental influences. This section examines two key management practices relevant to these questions – castration and shelter provision – that leave identifiable signatures in the zooarchaeological record and provide important insights into past animal husbandry regimes.

3.2.3.1 Castration

The deliberate castration of male domesticates has been employed in animal husbandry for millennia and represents one of the most profound human interventions affecting skeletal development (see Adcock 2022; Chahoud et al. 2023; Davis 2000; Price and Wolfhagen 2024; Zeder 2015). This management practice serves several practical purposes, including reproductive regulation, reduction of aggressive behaviors, and improvement of various animal products from meat texture to wool quality and working capacity. Testicular removal creates specific and identifiable changes in skeletal growth patterns, most notably affecting horncore development and the timing of limb bone maturation.

Historical Context and Purposes of Castration

Castration has been a standard husbandry practice across most agricultural societies, serving several economic and management functions (Kazantzis and Albarella 2016). Castrated males (wethers in sheep, steers in cattle) remain more manageable than intact males, particularly during breeding seasons when hormonal influences can make uncastrated animals aggressive and difficult to control (Grau-

Sologestoa and Albarella 2019). Wethers and steers can be kept in larger groups without the social disruption intact males might cause, allowing for more efficient resource utilization and simplified herd management (Harrison 2009).

Beyond behavioral advantages, castration significantly affects the quality of secondary products (Sherratt 1981). In meat production, castrates typically develop more evenly distributed fat and more tender meat than intact males, whose meat can develop strong flavors and tougher textures, particularly as they mature. For wool-producing sheep, wethers often yield wool of more consistent quality than rams, whose seasonal hormonal fluctuations can affect fiber development (Fraser 1951; Grau-Sologestoa and Albarella 2019). For working cattle, the greater docility of steers makes them more suitable for draft purposes than bulls, while their extended growth period potentially yields larger animals better suited to traction (Howard 1963; Thomas et al. 2013).

The archaeological evidence for castration extends deep into prehistory, with historical documents from classical periods onward providing explicit descriptions of castration practices and their purposes (Davis 2000). The identification of castrates in archaeological assemblages provides important insights into the sophistication of past husbandry regimes and the specific economic priorities of different communities.

Effects on Horncore Development

In horned species, particularly sheep, castration produces distinctive and often dramatic effects on horncore development. These effects range from complete absence of horncores to an appearance more similar to ewes than rams, or in some

cases, just slightly reduced size compared to intact males (Hatting 1975, 1983). These morphological outcomes vary according to both genetic factors and management decisions, with castration performed at younger ages generally producing more significant developmental disruption. Genetic predisposition also plays a role, as castrated individuals born from hornless mothers show the greatest probability of hornlessness (Clutton-Brock et al. 1990).

Beyond changes in size and shape, castration produces several diagnostic non-metric alterations in horncore bone structure. The bone surface becomes smoother, the core walls become thinner, and the internal cavities enlarge (Hatting 1975, 1983). These characteristics provide potential diagnostic features for identifying castrates in archaeological assemblages where horncores are preserved, though the variability in horn expression across different breeds and at different castration ages introduces some interpretive challenges.

Effects on Bone Growth and Fusion Timing

The horncore is not the only skeletal element affected by castration. Maturation of the entire skeleton, principally the fusion of epiphyses, is significantly delayed in castrates compared to intact males (Davis 2000; Hatting 1983). Hatting (1983) observed that long bone fusion could be delayed by over a year in some castrates compared to intact animals. Davis (2000) similarly noted that while bone fusion timing was highly variable, it generally occurred much later in wethers, with some examples showing delays exceeding one year.

Interestingly, tooth eruption appears largely unaffected by castration, although tooth wear can be reduced in castrates compared to rams (Hatting 1983). This reduced wear likely results from lower food intake in castrates than in intact males, as rams require greater energy intake, particularly before the mating season (Davis 2000). The difference in tooth wear between rams and wethers increases with age and this differential pattern between dental development and skeletal maturation provides another potential diagnostic marker for identifying castration practices in archaeological assemblages (Worley et al. 2016).

Clutton-Brock and colleagues' (1990) study of the Soay sheep found less conclusive evidence for significant delays in bone fusion caused by castration, though they acknowledged this might reflect limitations in their comparative material. The variability in observed effects highlights the complex interaction between castration, genetics, nutrition, and other environmental factors in determining the precise skeletal response to this practice.

Effects on Bone Dimensions and Proportions

The delayed epiphyseal fusion in castrates allows for an extended growth period, resulting in longer limb bones (Üstündağ and Kartal 2024). It is important to note that castration does not accelerate limb growth; studies of cattle (Lazzaroni and Biagini 2008) and goats (Koyuncu et al. 2007) found no difference in leg length between castrated and intact males when slaughtered at the same age (18 months). However, differences emerge in the length of mature (fully fused) long bones, as

documented by both Davis (2000) and Clutton-Brock and colleagues (1990) for sheep, and by Howard (1963) for cattle.

In both sheep and cattle, castrates typically develop the longest limb bones compared to intact males and females (Chen et al. 2022). Clutton-Brock and colleagues (1990) observed that the skeletal extremities – the facial region and lower limbs – appeared most affected by castration. This observation finds partial support in Davis' (2000) data, which showed that the radius, metacarpal, femur, tibia, and metatarsal all exhibited a 7% increase in length compared to rams, with the metatarsal showing a slightly greater increase of 8%.

Castration also affects bone breadth (width). In sheep, while limb bone length is typically greatest in castrates and shortest in ewes, bone breadth is generally largest in rams and smallest in ewes, with wethers intermediate. These differing length-to-breadth ratios create distinctive bone shapes across the three "sexes": ewes develop short, slender bones; rams develop tall, broad bones; and wethers develop tall, slender bones (Davis 2000). The same pattern appears in cattle, with cows, bulls, and steers showing parallel differences (Howard 1963).

The decreased bone breadth in wethers compared to rams may relate to nutritional factors. Koyuncu and colleagues (2007) observed that daily live weight gain in goat kids free to feed at their leisure was lower in castrates than intact males. Haddad and colleagues (2006), studying Awassi lambs, found no difference between intact males and castrates in carcass weight or average daily gain, but noted differences in feed utilization efficiency – rams made better use of consumed food than castrates. This suggests that nutrition, or at least the ability to utilize nutrients,

may partially explain castration's delay of bone fusion, creating complex interactions between this management practice and the nutritional factors discussed above.

Detecting Castrates in Archaeological Assemblages

Identifying castrates in archaeological assemblages presents significant methodological challenges but offers valuable insights into past husbandry practices (Albarella 1997; Cossette and Horard-Herbin 2003). Through analysis of metapodial dimensions, Howard (1963) developed an approach using calculated indices that express bone breadth as a percentage of bone length to differentiate between female, male, and castrated cattle. While this method achieved reasonable differentiation between females and intact males with minimal measurement overlap, castrate measurements posed greater difficulties, frequently overlapping substantially with female ranges and partially with male distributions, limiting the effectiveness of simple indices for reliable identification. More sophisticated visualization techniques employing scatter plots that compare breadth-to-length indices against absolute length values have demonstrated improved, though still incomplete, separation of the three reproductive categories (Cussans 2010; Davis 2000). Though this approach may not permit definitive classification of individual specimens as castrates, it enables zooarchaeologists to estimate the overall reproductive composition within faunal assemblages. When Davis (2000) attempted to apply this methodology to archaeological material from Launceston Castle, he encountered difficulties in determining sexual composition because the specimens represented larger animals than his Shetland sheep reference collection. This highlights the importance of

appropriate comparative data, suggesting that application to North Atlantic assemblages might prove more successful given their dimensional similarities to the Shetland reference populations.

In some cases, castration evidence appears through element-specific patterns. Popkin and colleagues (2012) noted that their Sheep Project found certain distal breadth measurements (particularly in the astragalus, tibia, and humerus) showed significant differences between intact males and castrates, while others did not. These findings suggest that targeted measurement strategies focusing on specific elements and dimensions might provide more reliable indicators of castration than general size assessments.

Horncore morphology can provide another diagnostic approach, with the distinctive changes in both external dimensions and internal structure noted by Hatting (1975, 1983) offering recognizable patterns. However, the variable expression of horns across different breeds complicates this approach in mixed archaeological assemblages, particularly as hornlessness can occur in females, males, and castrates depending on breed characteristics.

The presence of unusually long yet slender limb bones in an assemblage, particularly when combined with other demographic indicators suggesting selective male retention beyond typical meat production age profiles, may suggest castrate presence. This pattern would be particularly meaningful in contexts with evidence for wool production or traction (in cattle), where castrates offered specific economic advantages.

Castration Evidence in Icelandic and North Atlantic Contexts

Icelandic historical records document castration as a standard practice for both sheep and cattle management, with wethers kept primarily for wool production and some steers maintained for traction (McGovern et al. in press). The practice served the same range of purposes as elsewhere in Europe: controlling reproduction, improving manageability, and enhancing product quality (Thomas et al. 2013).

Archaeological evidence for castration in Icelandic assemblages remains limited but suggestive (Harrison 2009). The retention of older male sheep at some sites, beyond ages typical for meat production, suggests wether exploitation for wool. Júlíusson (1997) notes that historical sources indicate that cattle, particularly steers, represented valuable commodities for both traction and meat production in medieval and post-medieval Iceland. However, the definitive identification of castrates through osteometric analysis requires larger datasets than have typically been available from most Icelandic sites (Hambrecht 2012).

Broader North Atlantic evidence suggests that castration patterns may have varied between settlements and over time, potentially reflecting adaptation to different environmental conditions and economic priorities (Cussans 2017). In Norse Greenland, the increasing focus on woolen textile production suggested by archaeological evidence would have likely involved wether management, though the diminishing bone sizes over time might mask some of the distinctive castrate morphological signals through combined nutritional and environmental effects (McGovern 1985).

3.2.3.2 Provision of Shelter

The provision of shelter constitutes an important husbandry intervention that influences livestock skeletal development. As homeothermic organisms, all mammals, including domesticated species, must maintain stable internal temperatures despite environmental fluctuations. Sheep specifically function most efficiently within a thermal range of approximately 4-20°C (McArthur 1991). When environmental conditions fall outside this optimal zone, animals must redirect energy resources from growth processes toward thermoregulation (McArthur 1991; Smith 1964). This energy diversion becomes especially pronounced during exposure to precipitation and wind, which substantially accelerate heat loss. Consequently, in management systems where animals experience regular exposure to challenging weather conditions without adequate protection, skeletal formation potentially suffers as metabolic resources are prioritized for thermal maintenance rather than developmental processes.

Thermal Regulation and Energy Expenditure

The interconnection between protective structures, energy preservation, and developmental outcomes was quantitatively assessed through computational modeling by Higgins and Dodd (1989). Their model evaluated bovine growth trajectories under meteorological conditions recorded across several Scottish locations, analyzing performance across five winter seasons while contrasting unsheltered outdoor cattle against those provided with indoor housing. Nutritional inputs were standardized to achieve consistent daily growth targets of 0.75kg. Their

findings revealed substantial live-weight disparities between sheltered and exposed animals, with the most severe differential (73kg) occurring under the particularly challenging conditions recorded at Kirkwall (Orkney), attributable primarily to elevated wind velocities. When the simulation parameters incorporated enhanced nutrition (targeting 0.9kg daily gain), the performance gap narrowed considerably to just 16kg between fully exposed and completely sheltered individuals (Higgins and Dodd 1989). This demonstrates the compensatory relationship between nutritional enhancement and environmental stress, highlighting the significant interaction between shelter availability and nutritional status as external growth determinants.

The study also examined two intermediate shelter types: roof-only and walls-only structures (Higgins and Dodd 1989). Both reduced the weight deficit to some extent, but walls-only shelters proved more efficient, reducing the live-weight deficit to 15.6 kg on the lower plane of nutrition and to just 2.4 kg on the higher plane of nutrition under Kirkwall conditions. These findings suggest that providing shelter, particularly wind protection, would reduce heat loss and “improve the efficiency with which the animals use feed for productive purposes” (McArthur 1991), thereby decreasing the need for supplemental fodder during adverse weather.

Empirical research referenced by Higgins and Dodd (1989) indicated that completely housed cattle demonstrated superior weight development compared to those maintained in walled enclosures without roofing, although these differences did not achieve statistical significance (Cussans 2010). This result corresponds with the prediction of the model that lateral protection represented the most effective partial

shelter configuration, second only to complete environmental enclosure (Higgins and Dodd 1989).

Effects on Bone Morphology

While extensive research has documented shelter's effects on overall growth and weight gain, its specific impact on bone morphology remains less thoroughly studied. In the absence of direct empirical data, the most reasonable estimate is that shelter deprivation would produce effects similar to those of nutritional limitation (see Section 3.3.2), as both conditions effectively reduce the energy available for growth. However, since shelter primarily affects energy utilization rather than intake, the effects might manifest slightly differently from pure nutritional restriction.

One specific skeletal consideration relates to Allen's rule (discussed in Section 3.3.1), which states that animals in colder environments develop shorter extremities to reduce heat loss. For animals consistently exposed to cold conditions without adequate shelter, this adaptive response might manifest in relatively shorter limbs compared to sheltered contemporaries, even if both groups received similar nutrition. This direct temperature effect would operate alongside the indirect nutritional effects resulting from increased energy expenditure on thermogenesis.

It should be noted that while overall live weight may be significantly affected by shelter access, skeletal growth would likely experience less severe impact due to its early-maturing status, as discussed in Section 3.3.2. The skeleton receives preferential allocation of available resources compared to later-developing tissues like

muscle and fat, potentially buffering it somewhat against environmental stressors related to shelter deprivation.

Historical Evidence for Livestock Housing in Iceland

Historical records provide substantial evidence for livestock housing practices in Iceland and the broader North Atlantic region (Cussans 2010; Dugmore et al. 2012; Edwald Maxwell 2023; McGovern et al. 2007). The medieval Icelandic law code *Grágás* included specific provisions regarding the housing of livestock and required farmers to construct adequate shelters for their animals by a specific date (Dennis et al. 1980). Medieval sagas frequently mention byres and sheep houses as standard farm features, suggesting established norms for livestock shelter by the medieval period (Adalsteinsson 1990).

Later historical accounts emphasize the critical importance of livestock housing for winter survival (McGovern et al. in press). The eighteenth-century agricultural improver Björn Halldórsson advocated for better housing construction to reduce fodder requirements, explicitly recognizing the relationship between shelter provision and feed efficiency (Halldórsson 1948, in Hambrecht 2011; Hicks 2019). Travel accounts frequently mention livestock byres as integral components of Icelandic farms, though some also note regional variations in housing practices (Hicks 2019).

The severe consequences of inadequate shelter were documented repeatedly in historical records describing livestock losses during harsh winters (McArthur 1991; Ogilvie and Jónsdóttir 2000; Smith 1964). During the “Hard Years” of 1752-1759,

thousands of sheep died in exposed winter pastures, prompting reforms in sheep management that emphasized improved shelter provision (Ogilvie 1984). Similar events recurred throughout Icelandic history, reinforcing the critical relationship between adequate shelter and livestock survival in this marginal environment (Hicks 2019; Jónsson 1993).

Different shelter practices developed for various livestock species (Simpson et al. 2004; Thompson and Simpson 2007). Cattle were typically housed in substantial byres for the entire winter period, while sheep might be housed only during the most severe weather or snow cover, depending on regional practices (Adalsteinsson 1990). This differential treatment likely reflects both the relative economic value of the different species and their varying adaptability to winter conditions, with the more cold-tolerant sheep requiring less substantial protection than cattle.

Archaeological Evidence for Livestock Housing

Archaeological excavations have uncovered substantial evidence for livestock housing from the earliest settlement period in Iceland (Berson 2002; Hambrecht 2012; Parigoris 2022). At Hofstaðir, a large byre structure provided substantial cattle housing from the tenth and eleventh centuries (Lucas 2009). Similar structures have been identified at numerous other sites, including Sveigakot (Vésteinsson et al. 2005), Stóra-Seyla (Cesario 2021), and Gröf (Milek 2012). These structures typically feature central drainage channels and side aisles with evidence for stalling, following patterns well-established in Scandinavian building traditions.

Geoarchaeological analyses have confirmed these structures' function through identification of characteristic dung deposits, elevated phosphate levels, and other biochemical signatures associated with livestock housing (Milek 2012; Simpson et al. 2004). The substantial investment in these structures demonstrates the importance placed on livestock shelter from the earliest settlement phase.

Archaeological evidence also suggests changes in housing practices over time (Parigoris 2022). At some sites, early phase livestock housing appears less substantial than later structures, potentially indicating adaptive responses to environmental conditions as settlers gained experience with the Icelandic climate (McGovern et al. 2007). Other sites show evidence for periodic rebuilding and expansion of livestock housing, suggesting ongoing investment in shelter infrastructure (Lucas 2009).

The remains of sheep houses appear less frequently in the archaeological record, possibly reflecting both their typically lighter construction and the less consistent housing of sheep compared to cattle. However, some sites preserve evidence for substantial sheep housing structures, particularly in regions known for harsh winter conditions (Brewington et al. 2015).

Relationship to Bone Morphology in Archaeological Assemblages

The archaeological evidence for differential shelter provision potentially correlates with morphological patterns observed in faunal assemblages. The consistently larger size of cattle compared to contemporaneous European examples at some early Icelandic sites might partially reflect the substantial shelter investment evident in archaeological structures, which would have reduced environmental stress

despite the challenging climate (McGovern et al. 2007). However, this pattern is complex and likely reflects multiple interacting factors, including selective retention of larger animals during initial livestock introductions.

The better-preserved sheep remains at Hofstaðir compared to the more marginal Sveigakot site might partially reflect differences in shelter provision, as suggested by the more substantial farm infrastructure at the higher-status Hofstaðir site (McGovern et al. 2009). However, separating shelter effects from broader nutritional and management differences between these sites remains challenging.

In Norse Greenland, Cussans (2017) suggested that the apparent resilience of goats compared to sheep during periods of climate deterioration might reflect differential shelter provision, with goats potentially receiving preferential indoor housing. This hypothesis draws on both zooarchaeological evidence and ethnographic parallels from other North Atlantic communities, though direct archaeological evidence for species-specific housing practices in Greenland remains limited.

The complex interactions between shelter provision and other environmental and management factors make isolating its specific morphological effects challenging in archaeological contexts. However, incorporating shelter considerations into interpretations of faunal assemblages adds an important dimension to understanding how past communities managed livestock in marginal environments.

Summary of Human Management Practices

Human management practices like castration and shelter provision represent direct anthropogenic interventions that significantly affect livestock morphology.

Unlike the intrinsic genetic factors discussed in earlier sections, these extrinsic factors result from specific human choices about animal management, creating distinctive skeletal signatures that can be identified in archaeological assemblages.

Castration produces characteristic effects on bone development, particularly delayed epiphyseal fusion resulting in longer but more slender bones compared to intact males. These effects interact with both genetic factors (sexual dimorphism) and other extrinsic influences (nutrition), creating complex morphological patterns requiring careful contextual analysis. Identifying castrates in archaeological assemblages provides valuable insights into past breeding strategies, product specialization (meat, wool, traction), and herd management practices.

Shelter provision affects livestock morphology primarily through energy conservation, reducing the diversion of resources from growth to thermogenesis in challenging environments. This practice interacts particularly strongly with nutritional factors, as sheltered animals utilize feed more efficiently for growth rather than heat production. Archaeological evidence for livestock housing demonstrates substantial investment in shelter infrastructure, particularly for cattle, suggesting recognition of its importance for both animal survival and production efficiency.

Both practices reflect human adaptation to environmental constraints, particularly in marginal settings like Iceland where climate posed significant challenges to livestock management. The archaeological evidence for these practices demonstrates sophisticated understanding of animal physiology and careful management strategies designed to maximize production efficiency under challenging conditions. Recognizing their morphological effects enhances interpretations of

faunal assemblages, providing a more nuanced understanding of past human-animal relationships.

3.3 Interaction Between Factors

The preceding sections have examined individual factors affecting domestic mammal morphology, categorized as either intrinsic (sex, breed) or extrinsic (biogeography, nutrition, human management). However, in reality, these factors rarely operate in isolation. Instead, they interact in complex ways, sometimes amplifying, sometimes counteracting, and often modifying each other's effects on skeletal development. Understanding these interactions is essential for accurately interpreting skeletal remains from archaeological contexts, where multiple influences have typically shaped the morphological patterns observed in faunal assemblages.

3.3.1 How Intrinsic and Extrinsic Factors Interact

The interplay between intrinsic and extrinsic factors creates complex morphological responses that can be challenging to disentangle in archaeological assemblages. This section explores some of the most significant interactions, focusing particularly on those relevant to North Atlantic contexts.

Sex and Nutrition Interactions

Sexual dimorphism represents a fundamental intrinsic factor shaping bone morphology, but its expression can be significantly modified by nutritional status. Pálsson and Vergés (1952a) demonstrated that nutritional plane affects males and

females differently, with male skeletal development generally showing greater sensitivity to nutritional constraints. When comparing high and low nutritional planes, the differences between male and female skeletal proportions varied substantially. Under severe nutritional restriction, the typical pattern of male skeletal robusticity can be diminished or even reversed, with females occasionally developing relatively more robust bones than undernourished males.

The English Heritage "Sheep Project" found that nutrition's effects on bone dimensions varied significantly by sex (Popkin et al. 2012; Worley et al. 2016). While distal breadth measurements increased with improved nutrition across all sex categories, the magnitude of this effect differed, with females showing more consistent responses and intact males demonstrating more dramatic dimensional increases when provided with superior nutrition. This differential response creates an important interpretive challenge: changes in the degree of skeletal dimorphism might reflect nutritional shifts rather than genetic changes in a population.

For zooarchaeologists, this interaction mandates careful consideration of both factors when interpreting morphometric data. Bimodal distributions in measurement datasets might reflect sex differences, nutritional differences between management regimes, or some combination of both. This challenge becomes particularly acute in North Atlantic contexts, where marginal environments likely produced nutritional stress that would have modulated sexual dimorphism's expression, potentially creating patterns that differ from those observed in more favorable environmental settings.

Castration, Sex, and Nutrition

Castration represents a human intervention that directly modifies the expression of sexual characteristics, creating a "third sex" category with distinctive morphological traits. The impact of castration interacts with both original sexual dimorphism patterns and nutritional status. Davis (2000) documented how castrates develop longer but more slender bones than intact males, creating a pattern where ewes are short and slender, rams are tall and broad, and wethers are tall and slender. However, nutritional factors can significantly modify this pattern.

The Sheep Project observed that castrates responded differently to nutritional changes than either intact males or females (Popkin et al. 2012). While some distal breadth measurements showed significant increases with improved nutrition across all sex categories, others demonstrated no significant change in castrates despite substantial increases in intact males and females. This differential response suggests that castration not only alters growth patterns but also modifies how animals respond to other extrinsic factors like nutrition.

The interaction between castration and nutrition likely relates to the altered metabolic patterns in castrates. Koyuncu and colleagues (2007) found lower daily weight gain in castrated goat kids compared to intact males, despite ad libitum feeding, while Haddad and colleagues (2006) noted poorer feed conversion efficiency in castrated Awassi lambs. These observations suggest castration fundamentally changes how nutrition is utilized for growth, creating complex three-way interactions between sex, castration status, and nutritional plane.

For zooarchaeologists, these interactions create both challenges and opportunities. While they complicate straightforward interpretation of metric data, they also provide potential insights into past management regimes. For example, changes in castrate proportions relative to intact males and females might indicate shifts in economic focus (such as increased emphasis on wool or traction), while altered patterns of skeletal dimorphism across these three categories could suggest changes in feeding regimes or shelter provision.

Breed, Environment, and Human Management

Breed characteristics represent intrinsic genetic factors, but their expression and development are significantly shaped by environmental conditions and human management practices. Hammond (1932, in Cussans 2010) demonstrated that even within the same breed, animals raised on different nutritional planes developed dramatically different body proportions. This interaction is particularly important when considering how introduced livestock adapted to new environments during colonization episodes like the Norse settlement of Iceland and Greenland.

The adaptation of European livestock to North Atlantic environments represented a complex interplay between genetic selection, environmental constraints, and human management choices. Initial livestock introductions would have carried genetic characteristics suited to their regions of origin, but these traits would have been tested against new environmental challenges. Archaeological evidence suggests initial size increases in livestock following Norse settlement in both Iceland and Greenland (McGovern et al. 2007, 2009), potentially reflecting temporary

enhancement of the "annual productivity pulse" through landscape management. However, subsequent environmental deterioration, deforestation, and soil erosion created new constraints that interacted with both genetic factors and management practices to shape evolving livestock morphology.

Management responses to environmental challenges modified how breed characteristics were expressed in these settlements. The gradual shift from cattle-dominated to sheep-dominated economies reflected adaptation to environmental realities, as sheep could better utilize marginal grazing lands and required less winter fodder than cattle (McGovern et al. 2007, 2009). This shift represents a complex interplay between breed characteristics (the intrinsic adaptability of different species), environmental constraints (shorter growing seasons and reduced pasture quality), and human management decisions (selective culling, shelter provision, and feeding regimes).

Faunal evidence from Icelandic sites demonstrates how these interactions shaped livestock morphology over time. The more substantial sheep remains at Hofstaðir compared to the marginal Sveigakot site likely reflect a combination of genetic selection (preferential retention of larger, more robust animals at the higher-status farm) and management advantages (better nutrition and shelter provision) rather than just one factor in isolation (McGovern et al. 2009). Similarly, evidence for size increases in Icelandic cattle during the early modern period likely reflects both genetic improvements and enhanced management practices working synergistically.

Climate, Shelter, and Nutrition

The interactions between climatic conditions, shelter provision, and nutrition create particularly complex relationships affecting livestock morphology. While biogeographical principles like Allen's rule suggest direct temperature effects on extremity length, shelter provision can substantially modify these effects by creating microenvironments that buffer against climatic extremes. Simultaneously, both climate and shelter significantly impact nutritional efficiency, as unsheltered animals in cold environments must divert substantial energy to thermogenesis rather than growth.

The mathematical modeling conducted by Higgins and Dodd (1989) demonstrated how these factors interact. The live-weight deficit between sheltered and unsheltered cattle was substantially reduced when animals received higher-plane nutrition, showing how improved feeding could partially compensate for shelter deprivation. Conversely, shelter provision enhanced nutritional efficiency, allowing animals to direct more energy toward growth rather than heat maintenance. This interaction creates a situation where the absence of one factor (e.g., adequate shelter) can be partially offset by enhancement of another (e.g., increased feed provision), though at potential economic cost.

In Norse North Atlantic settlements, these interactions likely shaped livestock management strategies. Historical evidence suggests that Icelandic farmers recognized the relationship between shelter and fodder requirements, with agricultural writers like Björn Halldórsson advocating for improved housing to reduce feed needs (Halldórsson 1948, in Hambrecht 2011; Hicks 2019). Archaeological evidence for

substantial investment in livestock housing structures, particularly for cattle, suggests practical understanding of these interactions and deliberate management strategies to address them.

The seasonal dimension of these interactions creates particular challenges for interpreting archaeological assemblages. Seasonal fluctuations in both temperature and food availability would have created cyclical patterns of nutritional stress potentially offset by seasonal shelter provision. Depending on when animals experienced critical developmental phases relative to these seasonal cycles, different skeletal elements might show varying responses to these interacting factors. This temporal complexity adds another dimension to the already challenging task of disentangling multiple influences on skeletal morphology.

3.3.2 Regional Case Studies: Iceland and the North Atlantic

The Norse settlements of the North Atlantic provide particularly valuable case studies for examining how multiple factors interact to shape livestock morphology. These marginal environments, distant from the original source areas of domestic livestock, created distinctive adaptive pressures that tested both the genetic characteristics of introduced animals and the management strategies of their human keepers. This section examines how the interactions discussed above manifested in specific regional contexts.

Iceland: Adaptation and Management through Climatic Fluctuations

The settlement of Iceland (c. 870-930 CE) represented a significant biogeographical experiment, introducing northwest European livestock to a sub-arctic volcanic island with no prior grazing mammals. The initial settlement phase dramatically transformed the landscape through deforestation, creating an expanded but ultimately unstable grassland ecosystem that would shape livestock development for centuries to come (Dugmore et al. 2005; McGovern et al. 2007).

Archaeological evidence suggests initial success in livestock establishment, with relatively large animal dimensions at early settlement sites potentially reflecting both selective animal introductions and temporarily enhanced grazing conditions in newly created pastures (McGovern et al. 2007). However, subsequent environmental challenges – including soil erosion, volcanic eruptions, and climatic deterioration during the Little Ice Age – created complex selective pressures. These environmental challenges interacted with evolving management strategies, including changing shelter practices, fodder cultivation techniques, and breeding selection, to shape distinctive Icelandic livestock morphology.

Zooarchaeological evidence from different Icelandic sites illustrates how these interactions produced varied outcomes depending on local conditions. Sites like Hofstaðir, with substantial resource advantages including extensive wetland hay fields and substantial farm infrastructure, maintained larger livestock than more marginal settlements like Sveigakot (McGovern et al. 2009). These differences likely reflect complex interactions between intrinsic factors (selective breeding and

maintenance of preferred animals at higher-status farms) and extrinsic advantages (better nutrition and shelter provision).

The early modern period in Iceland saw further evolution in livestock morphology, with documentary and archaeological evidence suggesting modest size increases in cattle (Hambrecht 2011). These changes likely reflect interactions between improved husbandry practices, selective breeding, and adaptation to Iceland's distinctive environmental conditions. The presence of naturally polled animals carrying growth-related genetic markers (Utsunomiya et al. 2017) demonstrates how both natural and artificial selection shaped Icelandic livestock over the millennium following settlement.

Norse Greenland: Adaptation Under Severe Constraints

The Norse settlements in Greenland (c. 985-1450 CE) represent an even more extreme case of livestock adaptation to marginal conditions. Established at the northernmost limit of medieval European agriculture, these colonies maintained European livestock under severe environmental constraints, creating intense selective pressure and management challenges (Dugmore et al. 2012; McGovern 1985).

Archaeological evidence from these settlements demonstrates complex interactions between multiple factors shaping livestock morphology. Cussans (2017) documented increased caprine astragalus dimensions between earlier and later settlement phases (c. 1000-1300 CE), suggesting initial adaptation and management improvements. However, subsequent climate deterioration appears to have reversed

this trend, with later specimens showing reduced dimensions potentially reflecting both environmental stress and management limitations.

The differential response of sheep and goats to these challenging conditions illustrates how intrinsic species characteristics interact with environmental pressures and management practices. While both species showed some dimensional reduction over time, goats appear to have maintained their dimensions more effectively than sheep during periods of climatic stress (Cussans 2017). This pattern might reflect species-specific adaptive advantages, differential management (with goats potentially receiving preferential indoor housing), or some combination of these factors.

The eventual abandonment of the Greenland colonies in the fifteenth century demonstrates the ultimate limits of adaptation through the interaction of these various factors. Despite sophisticated management strategies, the combined pressures of climatic deterioration, economic challenges, and the inherent limitations of European livestock in this extreme environment eventually proved unsustainable (Dugmore et al. 2012). This outcome highlights how the interaction between intrinsic and extrinsic factors can create both adaptive opportunities and ultimate constraints.

Orkney and Shetland: Island Adaptations

The Northern Isles of Scotland present another valuable case study in livestock adaptation through interacting factors. These islands maintained distinctive livestock types from at least the Neolithic period, with archaeological evidence suggesting early development of the small, hardy breeds still found in the region today (Noddle 1974, 1978).

The distinctive North Ronaldsay sheep represents a particularly striking example of how intrinsic adaptability, environmental pressures, and human management interact to shape unique morphological types. Confined to the foreshore and subsisting almost entirely on seaweed – a diet extremely low in essential copper – these sheep developed distinctive biochemical and morphological adaptations (Tribe and Tribe 1950; Fenton 1997). While initially reflecting management decisions (beach confinement), these sheep eventually developed genetic adaptations to their unusual diet and environment, demonstrating how management practices can drive genetic change through selective pressure.

Archaeological evidence from sites like Skara Brae suggests that distinctive sheep types existed in Orkney from early periods, differing from mainland examples in both stature and specific anatomical features like femoral nutrient foramen position (Noddle 1978). These differences likely reflect the interaction between island biogeography (creating selective pressure for smaller, more resource-efficient animals), distinctive management practices (adapted to local environmental conditions), and genetic isolation (allowing distinctive adaptations to become fixed in island populations).

These case studies illustrate how multiple interacting factors shaped domestic livestock morphology across different North Atlantic settings. The varied outcomes in different locations highlight both the adaptive potential created through these interactions and the constraints they ultimately imposed on livestock development in these marginal environments.

Summary of Factor Interactions

The complex interactions between intrinsic and extrinsic factors create morphological patterns that cannot be understood by examining any single influence in isolation. Sex interacts with nutrition to create variable expressions of dimorphism; castration modifies both sexual characteristics and responsiveness to nutritional factors; breed characteristics develop differently under varying environmental and management regimes; and climatic conditions, shelter provision, and nutritional status create interwoven effects that collectively shape skeletal development.

These interactions have significant implications for zooarchaeological interpretation. Simple metric distinctions may reflect multiple interacting factors rather than single causes; changes over time might indicate shifts in management practices, environmental conditions, genetic selection, or combinations of these influences; and regional variations could reflect complex adaptive responses to local conditions rather than simply different livestock types or management approaches.

Understanding these interactions provides a more nuanced framework for interpreting faunal assemblages, recognizing that observed morphological patterns typically reflect multiple contributing factors whose relative importance may vary across different contexts. This integrated approach acknowledges both the adaptive potential created through these interactions and the constraints they ultimately impose on livestock development, particularly in marginal environments like the North Atlantic settlements examined in this research.

3.4 Conclusion

The examination of biological and environmental factors affecting domestic mammal morphology reveals the complex interplay between intrinsic genetic characteristics and extrinsic influences that shapes skeletal development in livestock. As this chapter has demonstrated, multiple factors – including sexual dimorphism, breed characteristics, biogeographical conditions, nutrition, and human management practices – contribute to the morphological patterns observed in archaeological assemblages. These factors rarely operate in isolation but interact in complex ways, creating distinctive signatures that can be identified through systematic biometrical analysis.

Sexual dimorphism represents a fundamental intrinsic factor, with male mammals typically developing larger and more robust skeletal structures than females, though the degree of dimorphism varies by species, element, and dimension. Breed characteristics introduce additional genetic influences, with selection creating distinctive morphological traits aligned with specific economic purposes. Biogeographical principles like Allen's rule, Bergmann's rule, and Geist's modification help explain how environmental conditions shape animal morphology through adaptation to temperature regimes and resource availability. Nutritional status significantly influences skeletal development, with different elements and dimensions showing varied responses to resource limitations. Human management practices like castration and shelter provision directly modify skeletal development through hormonal changes and energy conservation.

Understanding these factors and their interactions is essential for interpreting the biometrical patterns observed in the Skálholt assemblage. The morphological differences between cattle and sheep, the distinctive relationships between length and width dimensions, and the variations between different skeletal elements all provide valuable insights into past livestock management practices. By establishing this theoretical foundation, we can more effectively analyze how Skálholt's livestock morphology reflects the complex interactions between environmental constraints, cultural traditions, and elite status during the early modern period.

The analytical framework developed in this chapter will guide subsequent interpretations of biometrical patterns observed at Skálholt, helping to distinguish between environmental adaptations, management strategies, and potential engagement with broader European agricultural innovations. By systematically evaluating how different factors influenced livestock morphology, we can develop more nuanced understanding of how this elite ecclesiastical center navigated the challenging environmental conditions of early modern Iceland while potentially implementing innovative management practices that distinguished it from ordinary farms of the period.

Chapter 4: Social and Environmental History of Iceland and Skálholt

Iceland, a small island of approximately 103,000 km² in the North Atlantic, was one of the last landmasses on Earth to be permanently settled by humans. Seafaring Scandinavian agropastoralists first settled Iceland around 871 +/- 2 AD – a period known as *Landnám*, or "land-taking," which marked the beginning of significant anthropogenic impacts on the Icelandic landscape (Schmid et al. 2017; Vésteinsson and McGovern 2012). While place names and an early account by Dicuil, a ninth century monk and geographer, suggest an earlier ephemeral presence of a small number of Irish *papar* hermits on the island, no convincing material evidence of pre-Scandinavian settlement has been found (Tierney 1967).

Prior to human settlement, Iceland's ecosystem dynamics were primarily driven by climatic shifts and volcanic activity. The arrival of Norse settlers precipitated rapid and widespread ecological changes, fundamentally altering the island's environmental equilibrium (Catlin and Bolender 2018). This colonization process, which introduced both new species and land management practices, transformed Iceland's landscape through multiple interconnected mechanisms, ultimately reshaping both its ecological and socioeconomic structure. The most dramatic change involved extensive deforestation and subsequent soil erosion (Simpson et al. 2001; Streeter et al. 2015). Birch (*Betula* spp.) woodland cover, which originally encompassed approximately twenty-seven percent of the landscape, was systematically reduced to roughly one percent through clearing for grazing and

agriculture (Dugmore et al. 2009). While this transformation reduced biodiversity, it increased the biomass available for human exploitation through pastoralism and reshaped Iceland's agricultural and economic trajectories.

This process of environmental modification involved the establishment of rural societies based on husbanding imported livestock, marine fishing, and seasonal hunting. The introduction of grazing animals, namely sheep (*Ovis* sp.) and cattle (*Bos* sp.), led to widespread ecological changes through overgrazing and soil compaction. The movement of livestock between grazing areas, coupled with systematic hay production for winter fodder, established the foundation of Iceland's enduring mode of transhumant pastoralism (Bolender and Johnson 2018; Vidal-González et al. 2024).

Farmsteads were positioned in coastal and lowland valley areas with access to grazing resources, fisheries, and forests for fuel (Byock 2001, Simpson et al. 2003; Smith 1995; Vésteinsson 2000; Vésteinsson and McGovern 2012). This settlement pattern facilitated the development of complex resource networks extending beyond individual farmsteads, involved the exchange of essential resources such as fodder, marine products, and grazing access through the afrettir system of communal grazing lands (Schmid et al. 2017; Simpson et al. 2001). Despite geographic isolation, early Icelanders maintained active trade connections with northern Europe, notably through the export of walrus ivory – a high-status commodity that linked Iceland to broader Scandinavian commercial networks (Frei et al. 2015; Perdikaris and McGovern 2007, 2008).

The anthropogenic conversion of Iceland's woodland-dominated ecosystem into grasslands, heath, and wetland formations precipitated a level of social

restructuring. By the eighteenth century, approximately forty percent of rangeland grazing pastures exhibited severe degradation through erosional processes (Arnalds et al. 2001; Brown et al. 2012). The enhanced agricultural productivity derived from these transformed landscapes catalyzed nascent social stratification, as an oligarchic cohort of landowners and chieftains consolidated control over productive territories and instituted a tenant farming regime that perpetuated social disparities (Catlin 2019; Hicks 2019; Júlíusson et al. 2020).

The magnitude of these environmental modifications has led some scholars to describe Iceland as "one of the most degraded lands in Europe" (Simpson et al. 2004:471). This assessment encompasses both the extensive physical transformation of the landscape and the totality of the transition from an exclusively human-free ecology to an integrated social-ecological framework (Streeter et al. 2015). The transformation spanned several centuries, during which human-environment interactions became increasingly complex and self-reinforcing (Catlin 2019; Holling 1973; Streeter 2011).

4.1 Environmental Setting and Pre-Settlement Ecology

Prior to human settlement, the biotic composition of Iceland was characterized by limited diversity. The flora primarily consisted of birch (*Betula* sp.) and willow (*Salix* sp.) in a woodland/scrub mix in some places and a restricted array of grass (graminoid) and heath (ericaceous) species elsewhere. The pre-*Landnám* fauna exhibited similarly constrained diversity, with evidence suggesting the presence of a limited number of invertebrate taxa and fewer terrestrial mammals. Notably, both

Iceland and the Faroe Islands supported only two indigenous mammalian species: Arctic fox (*Alopex lagopus*) and polar bear (*Ursus maritimus*), which likely colonized these insular environments via transient ice bridges across the Denmark Strait during periods of extensive winter sea ice formation. In contrast, Greenland's pre-settlement fauna included caribou (*Rangifer tarandus*) and musk oxen (*Ovibus moschatus*), in addition to the coastal marine mammal species common to the region (Dugmore et al. 2005).

The arrival of agropastoralist humans precipitated a substantial transformation in Iceland's biodiversity. Norse settlers introduced a diverse assemblage of crops, livestock, and associated biota from northern Europe, including commensal mammals, insects, and herbaceous plants (Dugmore et al. 2005, 2012; McGovern et al. 2007). Dugmore and colleagues (2005:30) note that the Scandinavian settlers introduced so many plant species to Iceland that they probably increased the floristic diversity of the island while reducing the average number of species in specific areas due to soil erosion and overgrazing by livestock.

Grayson (2001) provides a comprehensive inventory of invertebrate translocations to Iceland, documenting the introduction of nineteen insect species, predominately those associated with livestock and cultigens, including ectoparasites such as the sheep louse and various coleopteran taxa. Of particular note is the sheep ked (*Melophagus ovinus* L.), known as *færilús* in Icelandic, which appears frequently in areas associated with wool processing (Konráðsdóttir et al. 2021). Its viviparous nature, with larvae cementing themselves to sheep wool, makes it a reliable indicator of woold cleaning activities (Cheyne et al. 1974). Recent work by Konráðsdóttir and

colleagues (2021) has analyzed fossil insect assemblages from Skálholt that highlight a continued presence of both human and sheep ectoparasites in areas of wool preparation in the post-medieval period. Comparative analyses with other Icelandic sites such as Stóraborg and Reykholt suggest that urine was commonly employed as a cleaning agent for wool and clothing to combat ectoparasite infestations, a practice that remained significant until the introduction of coal tar-based soaps in the late nineteenth century (Buckland and Perry 1989).

The most impactful introduction to Iceland was the domesticated livestock. At *Landnám*, the settlers introduced a standard northern European barnyard complement of cattle (*Bos taurus*), pig (*Sus scrofa*), sheep (*Ovis aries*), goat (*Capra hircus*), and horse (*Equus* sp.) along with the stalwart dog (*Canis familiaris*). These nascent farms were also the new homes to the accidental introduction of the commensal house mouse (*Mus musculus*). However, attempting to replicate continental European farming practices quickly and profoundly impacted the island landscape (Brown et al. 2012; McGovern et al. 2014; Simpson et al. 2002, 2004). Within the first few centuries of colonization, the Icelanders had begun clearing the woodland/scrub landscape for pastoral grazing and had initiated rapid soil erosion in various places across the coastal, habitable areas of the island. By the twelfth century, the shift in Icelandic agricultural strategies is evident in the faunal record, characterized by the virtual disappearance of pigs and goats from the zooarchaeological record and a recalibration of the sheep-to-goat ratio. This transition gave rise to the standard later medieval and early modern economy which was better adapted to the newly deforested landscape (Dugmore et al. 2005).

4.2 Settlement and Early History (c. 870-1300)

Iceland's political history is typically divided into several periods. The Settlement Period (*Landnámsöld*, ca. 870-930 AD) culminated in the establishment of a national assembly known as the Alþing and a common legal code known as *Grágás*. These institutions governed the Icelandic Commonwealth or Free State (*Þjóðveldið*), which lasted from approximately 930 to 1262/4 AD (Karlsson 2000).

The Commonwealth's political structure was decentralized, with power distributed among numerous chieftains (*goðar*) who held authority within their respective regions (*goðorð*). This system was rooted in personal allegiances and kinship ties, providing a framework for social organizations and political representation (McGovern et al. 2007). While early Icelandic society exhibited relative equality among households during the initial settlement phase, the Commonwealth period saw a gradual shift toward a more hierarchical social structure, driven by intensified land use, the growing power of the *goðar*, and integration into broader trading networking during the eleventh century.

Several significant milestones occurred throughout the Commonwealth Period, including the adoption of Christianity as the national religion around 1000 AD and the institution of the tithe in 1096. An increasingly robust parish system fed into bishop's seats at Holár in the north and Skálholt in the south (Lucas and Snæsdóttir 2022). Notably, Skálholt accumulated substantial landholdings through acquisitions, donations, and fines, owning approximately sixty properties by the middle of the thirteenth century and establishing itself as a major economic force in medieval Iceland. This accumulation began shortly after its establishment as Iceland's

first bishopric in the eleventh century, with a significant initial endowment from Gissur Ísleifsson, a powerful *goðar* and father of the first bishop, Ísleifur (Júlíusson et al. 2020; Lucas and Snæsdóttir 2022). Unlike chieftain properties that were frequently divided through inheritance, Skálholt's practice of retaining its acquired holdings led to steady growth through land purchases and ecclesiastical fines, allowing the estate to leverage its economic power on tithes, land rent, livestock leases, and even claims on resources such as driftwood and beached whales (Hambrecht 2011; Hambrecht and Gibbons 2018; Júlíusson et al. 2020; Lucas and Snæsdóttir 2022).

The period spanning the twelfth to fourteenth centuries witnessed a significant proliferation of literacy and literary production, as Iceland emerged as a relatively literate island population, resulting in a diversity of textual artifacts that include historical chronicles, annals, narrative sagas, law codes, *biskupasögur* (bishops' biographies), and other religious writing (Friðriksson 1994; Lucas and Snæsdóttir 2022; Vésteinsson 2000). Although often recorded long after the events they describe and influenced by oral traditions, these texts provide essential windows into medieval Icelandic society, revealing critical patterns in land ownership, legal systems, animal husbandry, population dynamics, and social hierarchies (McGovern et al. 2007). With this documentary evidence, scholars have recognized they must carefully consider how these texts may be shaped more by the era of their composition than by the historical periods they describe (Miller 1990). This rich corpus of medieval Icelandic literature subsequently became a focal point of scholarly inquiry for historians and literary critics specializing in the early medieval period (Byock 2001).

The Commonwealth experienced significant economic developments, particularly in trade, with increased demand for commodities like walrus ivory and dried fish connecting Iceland to broader economic networks (Frei et al. 2015; Hambrecht 2015; Perdikaris and McGovern 2008). The dried fish trade – predominately cod (*Gadus* sp.) – intensified during this period, leading to specialized fishing settlements and new economic opportunities while wool and hunting falcons provided additional valuable trade goods for European markets (Amundsen 2005; Boulhosa 2010; Hambrecht 2012). This period also saw the transformation of Iceland's landscape through domestication processes driven by ecological practices and social power dynamics, including the establishment of small, marginal sites occupied by low-status laborers who were instrumental in creating a pastoral landscape.

These laborers engaged in critical tasks such as land clearing, livestock herding, and resource extraction, establishing something of a "second nature landscape" - an anthropogenic environment fundamentally altered from its original state through human intervention and populated by translocated flora and fauna (cf. Catlin and Bolender 2018). The establishment of a "pioneer fringe" of low-status laborers was particularly crucial in this transformation, as they extended agriculture and modified the landscape under the direction of chieftains and powerful families who exercised control over the best lands and resources through established land tenure systems and legal codes (Dugmore et al. 2009). The shift from a forested landscape to a pastoral one, driven primarily by livestock grazing and deforestation,

had lasting ecological consequences, including significant soil erosion and changes in local biodiversity.

However, this transformation wasn't solely due to human activity but emerged from a complex interplay of environmental and social forces, including climate change and volcanic activity (Harrison and Maher 2014). Despite the initial environmental degradation, the landscape eventually stabilized into a sustainable agricultural system, demonstrating the resilience of this coupled social-ecological system that emerged during the Commonwealth period.

The Commonwealth came to an end following a period of civil war and strife known as the Age of the Sturlungs (*Sturlungaöld*, ca. 1180-1264), characterized by internal conflicts and power struggles among influential Icelandic families (*ætt*). This period of instability ultimately led to Iceland becoming subject to Norwegian rule, and then to Danish rule after the Kalmar Union in 1397 (Karlsson 2000).

4.3 Medieval to Early Modern Transition (c. 1300-1600)

The period between 1264 and 1602 represents a critical transitional phase in Iceland's environmental and sociopolitical trajectories (Catlin 2019; Eddudóttir et al. 2020). Environmental records indicate a pronounced shift from the Medieval Warm Period to the Little Ice Age, with initial climatic deterioration manifesting in the late twelfth century and intensifying through distinct cold intervals around 1280-1300 and 1350-1380 (Cesario 2019; Streeter 2012). The terminal sixteenth century experienced particularly adverse conditions, characterized by marked climatic variability that significantly affected both terrestrial agricultural productivity and marine resource

exploitation (Ogilvie 1992; Ogilvie and Jónsdóttir 2000; Ogilvie et al. 2009). Archaeological and paleoenvironmental evidence suggests that while the settlement period benefited from relatively favorable climatic conditions that supported extensive birch woodland coverage (approximately 27% of total land area), the progressive advancement of the Little Ice Age imposed increasingly challenging constraints on agricultural systems and livestock management regimes (Dugmore et al. 2007).

This environmental transformation occurred synchronously with fundamental political restructuring (Eddudóttir et al. 2020). The dissolution of the Icelandic Commonwealth in 1262-1264 followed the turbulent *Sturlungaöld* period, during which environmental stressors may have contributed to sociopolitical instability. Though documentary sources do not establish direct causal relationships between Little Ice Age conditions and civil unrest during the *Sturlungaöld*, the correlation between increasing climatic variability and greater social disfunction suggests complex interactions between environmental parameters and political dynamics (Buckland et al. 1996; Catlin 2019; McGovern 2000). The subsequent transition to Norwegian sovereignty, followed by incorporation into Danish administration under the Kalmar Union in 1397, fundamentally reconfigured Iceland's governance structure from autonomous self-rule to provincial status under external administration.

The economic sphere underwent equally significant transformations during this period, particularly in trade relations. The fourteenth century witnessed the emergence of the Hanseatic League as the dominant force in Iceland's economic

affairs, primarily focused on the North Atlantic cod trade operated through their Bergen hub (Dugmore et al. 2012; Júlíusson 2022). This economic pattern experienced temporary disruption during the "English Century" of the 1400s, when English merchants established direct commercial relationships with Icelandic communities (Jónsson 2021; Karlsson 2000). However, the Danish Crown's strategic allocation of exclusive trading privileges to Hanseatic merchants from Hamburg and Bremen effectively eliminated English competition and established precedents for the formal Danish Trade Monopoly instituted in 1602 (Hicks 2019; Martin 2022). Throughout these changes, Icelanders demonstrated remarkable adaptability in their response to both environmental and political challenges, maintaining subsistence strategies that combined pastoral farming with the exploitation of marine resources, even as the Little Ice Age altered traditional patterns of resource availability (Cesario 2021; McGovern et al. 2007; Streeter et al. 2012).

Iceland's position at the convergence of polar and North Atlantic currents makes it particularly vulnerable to climatic fluctuations (Sveinbjarnardóttir 2018). Cooling periods substantially impacted growing seasons, especially in northern Iceland's agricultural zones. Increased storminess, documented in both historical records and ice core data, disrupted fishing activities and maritime trade networks (Ogilvie and Jónsdóttir 2000; Dugmore et al. 2007). The seventeenth and eighteenth centuries saw considerable climate variability. While not uniformly cold, this period experienced several pronounced cold intervals, particularly during the 1620s-1640s and later in that century. Paleoclimatic reconstructions indicate that southern Iceland,

including the episcopal center at Skálholt, generally experienced comparatively milder conditions than other regions (Ogilvie 1992, 1997).

In addition to the challenges of adapting to climatic fluctuations, Iceland faced recurring epidemics and volcanic activity. Catastrophic smallpox epidemics killed an estimated twenty-six percent of the population in 1707-1709, with subsequently smaller death tolls in 1762-1763 and again in 1785-1787 (Hambrecht 2011; Vasey 1996). The Laki eruption of 1783-1784 triggered the "Famine of the Mist," resulting in significant loss of life among both humans and livestock. This eruption was particularly impact for Skálholt, as an earthquake in 1784 destroyed most of the bishop's manor complex (Demarée et al. 2001; Eggertsson 1998; Hambrecht 2011; Vasey 2002).

4.4 The Early Modern Period and Agricultural Change (c. 1600-1800)

4.4.1 The Danish Trade Monopoly and Its Effects

In 1602, Denmark instituted a trade monopoly with the intention of centralizing all of Iceland's trade through Copenhagen by 1620. The monopoly designated between twenty and twenty-five Icelandic harbors as seasonal trade centers, with merchants prohibited from overwintering to prevent the formation of fishing and trading villages (Róbertsdóttir 2014). While intended to stabilize prices, this system often resulted in Icelanders receiving less for their goods than middlemen merchants (Karlsson 2000).

The trade monopoly, which lasted until 1786, had significant implications for Iceland's economic and social development. It limited economic opportunities for most Icelanders and reinforced the power of large landowners like Skálholt. The monopoly conditions allowed the Danish crown to schedule trade with more consistency via specific harbors with centralized price fixing (Karlsson 2000).

The Danish Trade Monopoly transformed Iceland's socioeconomic structure and physical landscape for over 150 years (Martin 2022). By concentrating economic activities at designated trade harbors and privileging specific export commodities, the monopoly system created localized centers of commercial activity that substantially altered human-environment relationships throughout Iceland (Gunnarsson 1983; Hicks and Edwald Maxwell 2024). Through its focus on specific export commodities and centralized trade harbors, the monopoly created concentrated zones of economic activity that fundamentally altered how Icelanders interacted with their environment and each other (Hicks 2019).

Environmental degradation intensified under monopoly conditions, primarily through increased pressure on land resources to produce export commodities (Catlin 2019; Edwald Maxwell 2023). The monopoly's environmental impact was particularly evident in its intensification of landscape degradation. The demand for export commodities, especially dried fish and wool, put unprecedented pressure on Iceland's already vulnerable environment (Simpson et al. 2004; Streeter et al. 2015). This commercial pressure led to widespread winter grazing practices, where livestock were allowed to roam freely during the harsh winter months. While this practice helped conserve hay resources, it left the soil exposed precisely when it was most

vulnerable, accelerating erosion and creating barren areas across the landscape (Catlin 2019).

Icelandic communities developed sophisticated adaptive management systems in response to these environmental challenges (Brown et al. 2012; Simpson et al. 2001). Archaeological and documentary evidence indicates the implementation of structured regulations for summer communal grazing (*afréttir*), seasonal grazing at shielings, and presence of selective livestock breeding practices. These adaptive measures demonstrate local communities' capacity to negotiate the competing demands of commercial production and environmental sustainability within the constraints of monopoly-imposed economic structures (Catlin 2019; Hambrecht et al. 2018; Hicks 2019).

The monopoly's impact on social structures was equally profound. It created a deeply stratified society where large landowners and merchants controlled key commodities, while tenant farmers struggled under the weight of rents and tithes (Catlin 2019; Júlíusson et al. 2020). Tenant farmers, who made up a significant portion of Iceland's population, found themselves caught in a cycle of economic dependence, with limited access to markets and few opportunities for advancement (Gunnarsson 1983; Karlsson 2000).

4.4.2 The Second Agricultural Revolution and Iceland

The "Second Agricultural Revolution" represents a critical framework for understanding transformations in livestock management and breeding during the period coinciding with Skálholt's occupation (Overton 1996). Recent

zooarchaeological focus has also been given to a series of earlier agricultural developments during what has been termed the "long" sixteenth century (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013).

Traditional historical narratives placed the agricultural revolution primarily in the late eighteenth and early nineteenth centuries (approximately 1760-1840) (Hambrecht 2012). This framework emphasized the importance of parliamentary enclosures, technological innovations like Jethro Tull's seed drill, and the systematic livestock breeding improvements associated with innovators such as Robert Bakewell (Overton 1996). This period was characterized as enabling significantly increased agricultural productivity that sustained England's growing industrial population.

Revisionist historians, including Havinden (1961), Jones (1965), and notably Kerridge (1967), challenged this traditional chronology, arguing that significant agricultural innovations and productivity increases occurred much earlier – primarily in the sixteenth and seventeenth centuries (Allen 1999). Kerridge (1967) forcefully contended that many innovations traditionally attributed to the eighteenth century either did not originate in that period, were of limited significance, or had much earlier precedents. In this revisionist framework, the later eighteenth-century developments represented merely "finishing touches" to a revolution that had substantially occurred in earlier centuries.

A more nuanced approach has been proposed by Allen (1999), who distinguishes two separate agricultural revolutions. The first, preceding parliamentary enclosures, occurred before the mid-eighteenth century and was accomplished primarily by small-scale farmers working within open-field systems. Allen's analysis

documents significant output increases between 1520 and 1651 (see Thomas et al. 2013). The second revolution, according to Allen, occurred in the first half of the nineteenth century (1800-1850) and was characterized by accelerated growth in both output and productivity. Allen characterizes the second half of the eighteenth century – traditionally considered the core period of agricultural revolution – as a period of stagnation in agricultural development (Allen 1999).

While the Second Agricultural Revolution is most extensively documented in England, similar processes of agricultural change potentially occurred across the North Atlantic region, albeit with significant regional variations reflecting different environmental, economic, and political circumstances. Hambrecht (2012) began by applying concepts developed primarily in English historical contexts to the early examination of the Skálholt faunal assemblage.

Iceland's status as a remote colony with distinctive environmental challenges meant that agricultural innovations disseminated through different channels and at different rates compared to mainland Europe. The classic markers of agricultural improvement seen in England – enclosure, new crop rotations, mechanization – had varying relevance in the Icelandic context, where environmental constraints created different imperatives for agricultural adaptation. Hicks (2019) argues that the growth of record-keeping during this period, including hay reports, in Iceland's sheep economy brought modernization from Danish scientific advancements into Mývatnssveit in northern Iceland.

There is some documentary evidence to suggest that Icelandic elites, particularly at establishments like Skálholt, maintained connections with continental

European intellectual currents, including those related to agricultural improvement. The eighteenth-century agricultural manual *Atli* by Björn Halldórsson explicitly engaged with contemporary European agricultural improvement discourse, demonstrating awareness of emerging breeding principles and management techniques (Halldórsson 1948, in Hambrecht 2011). Evidence for experimental barley cultivation at Skálholt, documented through pollen analysis, further suggests engagement with European agricultural innovation (Einarsson 1982; Hambrecht 2011).

The timing of agricultural changes in Iceland necessarily differed from patterns observed in England. While English agricultural improvement gained momentum during the "long" sixteenth century, evidence for similar processes in Iceland appears more strongly during the seventeenth and eighteenth centuries (Hambrecht 2011, 2015). This chronological displacement potentially reflects both Iceland's peripheral position relative to European centers of innovation and the distinctive environmental and social conditions that shaped agricultural adaptation in the North Atlantic (Hambrecht 2011, 2012).

The zooarchaeological evidence from Skálholt provides a unique window into these processes of agricultural change and adaptation. Hambrecht's (2011, 2012) analysis of the Skálholt assemblage identified several distinctive features, including both naturally and artificially polled cattle specimens, unusual emphasis on beef consumption compared to typical Icelandic sites of the period, and evidence for traction use among cattle specimens. These patterns suggest engagement with broader

European agricultural improvement concepts, but adapted to Icelandic conditions and priorities. This dissertation serves to further advance this line of inquiry.

4.5 Modern Iceland (c. 1800-present)

The end of the Danish Trade Monopoly in 1787 marked a significant shift in Iceland's economic and environmental history (Hicks and Edwald Maxwell 2024; Hjálmarsson 2007; Martin 2022). As economic constraints began to loosen, more people gained access to international markets and wage labor opportunities (Edwald Maxwell 2023; Hicks 2019; Jónsson 2021). This period saw the re-inhabitation of many previously deserted farms and a near doubling of sheep numbers on the landscape between the beginning and end of the nineteenth century (Catlin 2019; Thórhallsdóttir et al. 2013).

However, this economic growth came at an environmental cost. Erosion, which had slowed dramatically since the eleventh century, began again in earnest (Arnalds 2005; Arnalds et al. 2001; Dugmore et al. 2009). The agricultural infrastructure that had supported sustainable practices for centuries was overwhelmed by the increased pressure on the land (Catlin 2019; Eddudóttir et al. 2020).

The nineteenth century also saw unprecedented growth in Iceland's human population. In 1801, there were around 47,000 people on the island. By 1860, this had increased to about 67,000 and by 1901, the population had reached 78,000 (Karlsson 2000). This growth was surpassed by the growth in livestock numbers. Between 1810 and 1854, the number of sheep in Iceland almost doubled (Thórhallsdóttir et al. 2013).

The agricultural infrastructures of early modern Iceland, including those managed by institutions like Skálholt, supported sustainable management of pastures and soils over centuries. These infrastructures connected the lives and labor of the earliest settlers to the choices made on the landscape over the next nine centuries. The walls, buildings, and productive soils that persisted through time facilitated sustainable practices within a fundamentally unequal social structure (Catlin and Bolender 2018).

However, as the Danish Trade Monopoly came to an end and economic structures began to change in the late eighteenth and nineteenth centuries, this infrastructure was overwhelmed (Hicks and Edwald Maxwell 2024). The combination of more farms and increasing international demand for Icelandic lamb and wool led to unsustainable pressure on the landscape (Edwald Maxwell 2023). The infrastructure that had invisibly supported agriculture at sustainable levels by preserving soils through centuries of active Danish control was no longer sufficient to prevent widespread erosion (Róbertsdóttir 2014; Thórhallsdóttir et al. 2013).

The zooarchaeological analysis from Skálholt provides a crucial window into this transition to early modern Iceland, offering material evidence for changes in livestock management coinciding with broader socioeconomic transformations (Hambrecht 2012, 2015). This research aligns with what Orser (2014) terms "modern-world archaeology," a framework that moves beyond traditional conceptions of historical archaeology to specifically address the post-1500 world. Unlike historical archaeology, which may broadly encompass the study of any literate society, modern-world archaeology focuses on examining what Orser (1996)

identifies as the “four haunts” of modernity: colonialism, capitalism, Eurocentrism, and racialization. This theoretical orientation provides valuable interpretive context for understanding how Skálholt’s livestock management practices reflected its position as an elite institution negotiating both local environmental constraints and broader European influences during Iceland’s integration into early modern economic networks.

4.6 Zooarchaeological Research in Iceland

The development of zooarchaeology in Iceland has been closely linked to broader archaeological investigations of Norse colonization and adaptation to the North Atlantic environment. Early zooarchaeological research in Iceland emerged in the mid-20th century, but it was not until the 1980s and 1990s that systematic analyses of faunal assemblages began to significantly contribute to our understanding of Iceland’s settlement history and environmental impacts.

The North Atlantic Biocultural Organization (NABO), established in 1992, has played a crucial role in coordinating zooarchaeological research across the North Atlantic region, including Iceland. This international research cooperative has facilitated standardized recording protocols, comparative analyses, and collaborative approaches that have substantially advanced our understanding of human-animal relationships in Iceland through time (McGovern et al. 2007).

Methodologically, Icelandic zooarchaeology has embraced a range of analytical approaches. Traditional taxonomic identification and quantification methods, including Number of Identified Specimens (NISP) and Modified General

Utility Index (MGUI), form the foundation of most analyses. However, researchers have increasingly integrated more specialized techniques, including biometrical analysis, stable isotope analysis, ancient DNA studies, and taphonomic investigations to address specific research questions (e.g., Hambrecht 2012; Hambrecht and Gibbons 2018; Hambrecht et al. 2022).

One of the distinctive features of Icelandic zooarchaeology is its strong integration with environmental archaeology and historical ecology. The combination of excellent preservation conditions in many Icelandic sites, high-resolution tephra dating sequences, and rich documentary records has enabled researchers to situate faunal evidence within precisely dated environmental and historical contexts. This integrative approach has been particularly valuable for understanding the complex interactions between human settlement, animal management, and environmental change (McGovern et al. 2007; Simpson et al. 2001).

Research themes in Icelandic zooarchaeology have evolved over time but have consistently addressed several key areas. The initial impact of Norse settlement on the island's ecosystems, documented through changes in faunal assemblages and associated environmental proxies, remains a central focus. Studies have examined the introduction of domestic livestock, shifts in husbandry practices, and the long-term sustainability of animal management strategies in Iceland's vulnerable landscape (Dugmore et al. 2005, 2012; McGovern et al. 2007).

The adaptation of livestock management to Iceland's challenging environment has been another significant research area. Zooarchaeological evidence has documented shifts in herd composition, particularly the decrease in pigs and goats

and the increasing dominance of sheep in Icelandic assemblages over time. These changes have been interpreted as adaptive responses to environmental conditions, especially deforestation and the expansion of pastureland (McGovern et al. 2009).

Social differentiation and economic specialization have also been explored through zooarchaeological analysis. Comparative studies of assemblages from high-status sites like Hofstaðir, Reykholt, and Skálholt versus more marginal farms have revealed differences in consumption patterns, access to resources, and involvement in specialized production and trade (Hambrecht 2011, 2012; McGovern et al. 2009; Pálsson 2019).

Marine resource exploitation, particularly fishing, has been extensively documented through zooarchaeological research. Studies have traced the development of Iceland's fishing economy from early settlement through the medieval and early modern periods, highlighting changes in species targeting, processing methods, and the relationship between fishing and farming in Iceland's mixed economy (Perdikaris and McGovern 2008; Hambrecht et al. 2022; Harrison et al. 2008).

Recent decades have seen increasing attention to the early modern and modern periods in Icelandic zooarchaeology. Research at sites like Skálholt has begun to address previously understudied periods, providing insights into how livestock management, consumption practices, and economic networks evolved during the post-medieval era (Hambrecht 2011, 2012; Pálsson 2019).

Despite these advances, Icelandic zooarchaeology faces several ongoing challenges. The uneven distribution of excavated and analyzed assemblages across

different regions and time periods creates gaps in our understanding. Additionally, methodological variation in recovery techniques, recording protocols, and analytical approaches can complicate comparative studies. Furthermore, while Iceland's documentary record provides valuable contextual information for later periods, integrating textual and zooarchaeological evidence remains a complex interpretive challenge.

Looking forward, Icelandic zooarchaeology continues to develop in several promising directions (see Hambrecht et al. 2020). Advanced biomolecular techniques, including ancient DNA analysis and proteomics, offer new possibilities for understanding livestock origins, breeding practices, and disease patterns. Stable isotope studies are providing increasingly nuanced perspectives on animal diet, management practices, and environmental conditions. Biometrical analyses, the focus of the present study, are contributing important insights into animal morphology, size change, and potential agricultural improvements through time.

The integration of zooarchaeological data with broader archaeological, environmental, and historical datasets remains a cornerstone of research in this field. This integrative approach, exemplified by the present study of the Skálholt assemblage, continues to enhance our understanding of Iceland's complex social and environmental history from settlement to the modern era.

4.7 Skálholt: Archaeological Context

Skálholt served as one of Iceland's two episcopal seats from 1056 until the end of the eighteenth century, making it a major center of religious, political, and

economic power throughout the medieval and early modern periods. Historical sources indicate that it was founded through a substantial land donation by Gissur Ísleifsson, marking the beginning of the bishopric's accumulation of land and wealth. Archaeological investigations at Skálholt have revealed the material dimensions of this historically documented power center, providing crucial insights into Iceland's social, economic, and environmental history.

The first systematic archaeological excavations at Skálholt took place between 1954 and 1958, focusing primarily on identifying the cathedral's architectural sequence and establishing the site's chronology. These early investigations yielded substantial faunal remains but were limited in their methodological approach and analytical scope. Archaeological work resumed in the 1990s with smaller-scale interventions, but it was the extensive excavation program conducted between 2002 and 2007 that provided the most comprehensive understanding of the site's material culture and stratigraphic sequence (Lucas and Snæsdóttir 2022).

This major research initiative concentrated on the seventeenth- and eighteenth-century phases of occupation, uncovering architectural remains of the bishop's residence, the Latin school, and numerous ancillary structures. The excavations revealed a complex settlement pattern characterized by specialized functional zones, substantial investment in built infrastructure, and material expressions of high-status consumption. Particularly significant for zooarchaeological research was the recovery of substantial midden deposits containing well-preserved faunal assemblages, especially from the eighteenth-century contexts (Hambrecht 2011).

Material culture recovered from Skálholt demonstrates the site's extensive connections to European economic networks and its role as a center of elite consumption. Imported ceramics, glass vessels, and specialized architectural elements reflect both the bishopric's economic resources and its cultural orientation toward continental European models. The material signature of high-status consumption is further reinforced by the faunal assemblage, which exhibits distinctive patterns of species representation and consumption practices compared to contemporary rural farmsteads (Hambrecht 2011, 2012).

The extensive building inventory at Skálholt, documented in historical records and partially verified through archaeological excavation, attests to the site's complex economic infrastructure. The presence of specialized storage facilities for various food products, workshop spaces, animal housing structures, and accommodations for a substantial resident population reflects the multifaceted economic functions of this ecclesiastical center. Archaeological evidence suggests that Skálholt maintained an elaborate system for managing and processing agricultural products from its extensive property holdings (Júlíusson et al. 2020).

The landscape context of Skálholt has been investigated through archaeological survey, revealing evidence of resource management beyond the settlement core. Field boundaries, irrigation features, and specialized production areas in the surrounding landscape demonstrate the bishopric's comprehensive approach to environmental management. The 2016 landscape survey identified various archaeological features related to livestock management, agricultural intensification,

and resource extraction, highlighting the spatial extent of Skálholt's economic influence (Lucas and Snæsdóttir 2022).

Zooarchaeological research at Skálholt has been particularly informative regarding the site's economic practices and consumption patterns. Preliminary analyses by Hambrecht (2011, 2012) identified several distinctive characteristics in the faunal assemblage, including an unusually high proportion of cattle remains, evidence for specialized breeding practices, and consumption patterns that differ markedly from contemporary rural sites. These findings suggest that Skálholt may have functioned as a center for agricultural innovation, potentially introducing or adapting European improvement practices within the Icelandic context.

The archaeological exploration of Skálholt contributes significantly to our understanding of post-medieval Iceland, a period that has been relatively under-researched archaeologically compared to the Viking Age and medieval periods. The material evidence from Skálholt provides insights into how this elite ecclesiastical institution negotiated the changing political, economic, and environmental conditions of early modern Iceland, maintaining its central position while adapting to new circumstances. The substantial zooarchaeological assemblage from the site offers a unique opportunity to investigate livestock management practices, consumption patterns, and potential agricultural innovations at one of Iceland's most powerful institutions during a critical transitional period.

4.8 Conclusion

Iceland's environmental and social history from settlement through the early modern period demonstrates the complex interplay between ecological change, social structures, and economic status. The initial settlement period saw rapid environmental degradation that paradoxically led to a more economically productive landscape. This transformed environment supported a sustainable, but highly unequal, social system for centuries.

The role of institutions like Skálholt in maintaining this system highlights the intricate relationships between land ownership, political power, and environmental management. As Iceland transitioned into the modern era, the breakdown of traditional economic constraints led to new opportunities but also renewed environmental challenges, illustrating the delicate balance between economic development and ecological sustainability.

This history provides valuable insights into the long-term consequences of human-environment interactions and the complex relationships between sustainability, social inequality, and economic systems. It underscores the importance of considering both ecological and social factors in understanding historical trajectories and in addressing contemporary environmental challenges.

The case of Iceland illustrates that sustainability and social justice are not necessarily aligned. While the Icelandic landscape achieved a form of ecological stability for centuries, this was accompanied by extreme social inequality. As modern economic forces began to transform Iceland in the nineteenth century, new

opportunities for social mobility emerged, but at the cost of renewed environmental degradation.

These observations raise important questions about the nature of sustainability and its relationship to social structures. They challenge us to consider how societies can achieve both ecological sustainability and social justice, and what trade-offs might be involved in pursuing these goals. As we face global environmental challenges in the present, the lessons from Iceland's past offer valuable perspectives on the complex interactions between human societies and their environments.

The forthcoming zooarchaeological analysis of the Skálholt assemblage will contribute to our understanding of these dynamics by examining how one of Iceland's most powerful institutions managed its livestock resources, potentially implemented agricultural innovations, and maintained its economic position within this evolving social-ecological system. By integrating zooarchaeological evidence with historical and environmental data, this research will add nuance to our understanding of Iceland's environmental and social trajectory through the early modern period.

Chapter 5: Materials, Methods, and Comparative Sites

This chapter presents the methodological framework employed to analyze faunal remains from Skálholt and comparative sites across the North Atlantic region. Through biometrical analysis of livestock remains, this research provides a quantitative perspective on agricultural practices, animal management strategies, and potential responses to environmental and socioeconomic changes in early modern Iceland. The methodological approach builds upon established zooarchaeological techniques while addressing the specific challenges and opportunities presented by the relatively well-preserved faunal assemblages from this elite ecclesiastical center.

The analytical strategy integrates several complementary techniques centered on biometrical analysis. Log-ratio scaling provides the foundation for standardized comparative analysis across sites, elements, and species by converting raw measurements to dimensionless values relative to standard reference specimens (Meadow 1999; Simpson 1941). This approach, further developed by Albarella (2002), Payne and Bull (1988), and more recently refined by Pozo et al. (2023), allows for the pooling of different skeletal elements to increase sample sizes while maintaining analytical rigor. Supplementary methods, including withers height estimation (Teichert 1975; von den Driesch and Boessneck 1974), slenderness index calculation (Guintard and Lallemand 2003), and wether identification techniques (Davis 2000; Popkin et al. 2012), provide additional lines of evidence to contextualize the biometrical data.

The comparative framework is deliberately structured to place Skálholt's faunal assemblage within multiple contextual scales: its internal spatial organization

(comparing elite household areas with midden deposits), its position within medieval and post-medieval Iceland (through comparison with sites like Gásir and Möðruvellir), and its broader North Atlantic setting (incorporating data from Greenland and Shetland). Additionally, the inclusion of central English material from The Shires enables examination of how the agricultural changes associated with England's '"long" sixteenth century' might relate to patterns observed at Skálholt (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013).

Through these methodological approaches, this work addresses key questions regarding livestock improvement, environmental adaptation, and the influence of elite status on animal management in early modern Iceland. The methods here are intended to detect evidence of deliberate breeding strategies, presence of imported stock, responses to environmental pressures, and variations in animal management practices that might reflect broader socioeconomic patterns in post-medieval Iceland (Hambrecht 2011, 2012). By integrating multiple analytical techniques within a regional comparative framework, this research contributes to our understanding of how elite institutions like Skálholt navigated the complex interplay between environmental constraints, cultural traditions, and external influences during a period of significant agricultural transition.

5.1 Data Collection

Vertebrate remains from Skálholt were collected during modern systematic excavations directed by Gavin Lucas and the Institute of Archaeology (*Fornleifastofnun Íslands*) from 2002 to 2007 (Lucas and Snæsdóttir 2022). The

excavations yielded substantial faunal assemblages originally comprising 50,928 bone fragments (Total Number of Fragments, TNF), with 6,232 specimens identified to species level (Number of Identified Specimens Present, NISP) (Hambrecht 2011). These assemblages primarily date to the site's last three centuries of occupation (ca. 1650-1950).

For the purposes of this research, two distinct archaeological contexts from Skálholt provide the primary faunal material for examination. Midden Zone C, particularly context [454], yielded exceptionally dense bone deposits near a documented meat storage facility where butchery activities likely occurred (Hambrecht 2011). This midden formed where multiple dumps of refuse, ash, and fill accumulated on a sloping knoll near one of the main entrances to the complex. The analyzed sample from this midden represents one of the larger measurable assemblages from Iceland, providing substantial material for biometrical analysis. The second primary context comprises interior spaces associated with the bishop's residence, referred to as "household" contexts. These specimens derive primarily from a storeroom near the Bishop's dining area and other furnished rooms - a relatively more high-status space by 1698 (Lucas and Snæsdóttir 2022). The comparative analysis of these distinct depositional contexts offers insights into potential differences in consumption patterns between elite and service areas within the ecclesiastical complex.

Initial analysis of these remains was conducted by George Hambrecht, then a graduate student in the Hunter College Zooarchaeology Laboratory with Thomas McGovern at the City University of New York, who collaborated with Jim Woollett

to produce a preliminary report in 2006 (Hambrecht et al. 2006). Further work on the faunal assemblage by Hambrecht has focused on the nature of Skálholt as a high-status site with unique opportunities available to it in relation to continental Europe during the early modern period (Hambrecht 2006, 2009, 2011, 2012, 2015). These analyses highlighted the site's distinctive pattern of beef consumption and cattle management and began the process of examining the biometrical data and use of a log-scaling index. Subsequent processing of additional material continued at the Zooarchaeology Laboratory at the University of Maryland with measurements recorded by the author, Hambrecht, and various students over time (Gibbons 2017).

The analysis of the Skálholt faunal collection was conducted at the Zooarchaeology Laboratories of Hunter College (City University of New York), Brooklyn College, and the University of Maryland. These analyses made use of the comparative skeletal collections at all three laboratories as well as the holdings of the American Museum of Natural History in New York City and the National Museum of Natural History in Washington, D.C. All specimens were identified as far as taxonomically possible, with postcranial elements measured following von den Driesch (1976) and tooth eruption and wear recording following Grant (1982).

In most Icelandic faunal assemblages, the majority of caprine remains are identified as "sheep/goat" rather than specifically as sheep (*Ovis aries*) or goat (*Capra hircus*). However, most comparative data from other studies are strictly identified as *Ovis aries*. Given that sheep are much more common than goats in Icelandic zooarchaeological assemblages from the Viking Age through the early modern period, a pattern consistently documented across North Atlantic sites

(McGovern et al. 2007), all caprines used in this analysis have been treated as *Ovis aries*. The normality of the data distribution for Skálholt suggests a relatively homogenous population of caprines, lending further support to this assumption.

Following NABO Zooarchaeology Working Group recommendations and the established traditions of North Atlantic zooarchaeology, the basis for most quantitative presentation is done with a simple count of Number of Identified Specimens Present (NISP). This approach facilitates comparative analysis across North Atlantic sites where similar quantification methods have been employed. Moreover, the nature of Norse farm middens, with their generally excellent preservation and relatively low fragmentation rates, makes NISP a more appropriate quantification method than Minimum Number of Individuals (MNI), which can artificially inflate the representation of rare species in well-preserved assemblages (Lyman 2008; Reitz and Wing 2008).

Digital records of all data collected were made following the ninth edition of the NABONE recording package (Microsoft Access database supplemented with specialized Excel spreadsheets). This standardized recording system, developed specifically for North Atlantic zooarchaeological research, ensures methodological consistency and facilitates comparative analysis across sites. The complete dataset, including primary measurements, derived indices, and analytical results, has been archived in this format and will be accessible to researchers through both the North Atlantic Biocultural Organization (NABO) digital archive (www.nabohome.org).

Comparative biometrical data have been aggregated from multiple published sources (Table 5.1). Biometric data has been recorded by colleagues working

island	site	region	description	phases & dates	references
Iceland	Sveigakot	Mývatn	farm with midden	late 9th-10th c. AD	McGovern et al. 2007; Cussans 2010
	Hrísheimar	Mývatn	farm with midden	late 9th-mid 11th c. AD	Edvardsson & McGovern 2007; Cussans 2010
	Hofstaðir	Mývatn	Viking Age hall	mid 10th-mid 11th c. AD	McGovern et al. 2009; Lucas 2009; Cussans 2010
	Steinbogi	Mývatn	farm with midden	ca. 1200 AD	McGovern 2002; Cussans 2010
	Gásir	Eyjafjörður	trading center	mid 13th-early 15th c. AD	Harrison 2008, 2009; Cussans 2010
	Möðruvellir	Eyjafjörður	farm with midden	16th-18th c. AD	Harrison 2007; Cussans 2010
	Skálholt	Biskupstungur	episcopal see	17th-18th c. AD	Hambrecht 2011, 2012; Lucas and Snæsdóttir 2022
Shetland	Old Scatness	South Mainland	post-med. crofting	17th-19th c. AD	Dockrill et al. 2013
Greenland	Western Settlement	Sermersooq	farms with middens	14th-15th c. AD	McGovern 1985
Britain	The Shires	East Midlands	Leicester city center	16th-17th c. AD	Lucas and Buckley 2007; Gidney 1991a, b, c, 1992, 1993; Grau-Sologestoa and

Table 5.1. Sites included in analysis.

elsewhere in Iceland within the North Atlantic Biocultural Organization (NABO) network, though the majority of work done to-date on the biometrical analyses of Icelandic faunal material has been undertaken by Julia Cussans (2010, 2017). In her doctoral thesis at the University of Bradford, Cussans (2010) presents a range of faunal linear biometrical data from sites across the North Atlantic in a combined database spanning from the Neolithic to the early modern period that includes some of the data from other Icelandic sites. Additional comparative material for cattle comes from the work of Grau-Sologestoa and Albarella (2019) in their reexamination of cattle elements from sixteenth and seventeenth century Leicester, England.

5.2 Skálholt Materials

All fragments were identified as far as taxonomically possible, with most mammal ribs, long bone shaft fragments, and vertebral fragments assigned to broader taxonomic categories: “Large Terrestrial Mammal” (cattle/horse size), “Medium Terrestrial Mammal” (sheep/goat/pig/large dog size), “Small Terrestrial Mammal” (small dog/fox size), and “Very Small Terrestrial Mammal” (rodent size). This approach aligns with standard zooarchaeological practices and facilitates comparative analysis across North Atlantic assemblages.

Measurements of mammal bones follow von den Driesch (1976), and mammal tooth eruption and wear recording follows Grant (1982). Measurements that were recorded by others in centimeters (cm) have been converted to millimeters (mm) and recorded to the nearest hundredth of a millimeter. Table 5.2 provides descriptions

of the measurement codes used for specific bone dimensions present in the Skálholt assemblage that are utilized in this study.

Summary statistics, including sample sizes, means, minimum and maximum values, standard deviations, and variances, were calculated for the Skálholt sheep and cattle measurements (Tables 5.3 and 5.4). These data serve as the foundation for all subsequent analyses in this study.

Table 5.2. Brief description of measurement codes used in this analysis. For detailed descriptions for individual elements see von den Driesch (1976).

dimension	description
GL	greatest length
Bp	breadth of the proximal end
SD	smallest breadth of the diaphysis
Bd	breadth of the distal end (in metapodials, 'BFd')
Glpe	greatest length of the lateral side (phalanx 1)

The sheep bone elements showing the greatest variation in the Skálholt assemblage (metacarpal, metatarsal, and radius lengths) are particularly responsive to factors that can influence overall bone size and shape, including sexual dimorphism, breed diversity, and environmental conditions affecting growth and development (Cussans 2010, 2017; Thomas et al. 2013; Wright and Viner-Daniels 2015). The notable degree of variance in these elements could reflect the presence of multiple sheep varieties at Skálholt and differing husbandry practices (Davis 2000; Pálsson and Vergés 1952a, b; Popkin et al. 2012). These specific elements are commonly well-preserved in archaeological contexts and provide reliable measurements for detecting subtle morphological variations within historical sheep populations.

Table 5.3. Summary statistics for Skálholt cattle.

element	measurement	*n*	mean	min	max	SD	var.
astragalus (AST)	Bd	4	37.88	37.50	38.70	0.568	0.323
calcaneus (CAL)	GL	7	106.97	56.60	120.00	22.502	506.342
metacarpal (MC)	GL	0					
	SD	0					
	Bd	2	55.20	53.70	56.70	2.121	4.500
	Bp	3	55.27	51.00	57.80	3.717	13.813
metatarsal (MT)	GL	3	193.97	190.90	199.00	4.394	19.303
	SD	3	23.50	21.50	25.50	2.000	4.000
	Bd	5	49.62	39.90	56.00	6.225	38.747
	Bp	7	43.49	38.60	47.60	3.294	10.848
phalanx 1 (PH1)	Glpe	14	50.44	29.40	62.20	10.750	115.552
	SD	13	22.89	19.50	25.50	2.025	4.101
	Bd	14	25.72	21.30	29.90	2.701	7.297
	Bp	11	25.69	21.70	30.30	2.375	5.641
humerus (HUM)	Bd	18	74.18	61.00	86.10	7.455	55.570
radius (RAD)	GL	0					
	Bp	0					
	Bd	12	73.96	64.50	83.00	5.850	34.226
femur (FEM)	Bd	13	78.66	40.25	94.02	12.695	161.167
tibia (TIB)	Bd	9	59.14	53.80	72.10	5.853	34.263
	total *n*	138					

The cattle bone elements showing the greatest variation in the Skálholt assemblage (calcaneus and phalanx 1 lengths) reflect complex social and biological factors in medieval Icelandic cattle management (Table 5.4). This variation could likewise stem from many similar influences, including the presence of different cattle breeds (particularly European polled varieties), pronounced sexual dimorphism between bulls and cows, and diverse husbandry practices involving differential winter foddering and grazing locations (Wright and Viner-Daniels 2015). However, as noted by Popovici and colleagues (2011), widths are generally better indicators than lengths for sexual dimorphism in cattle. The significance of this morphological diversity is

heightened by Skálholt's status as an elite ecclesiastical center, where European cattle breeds may have been deliberately introduced as part of broader agricultural innovations.

Table 5.4. Summary statistics for Skálholt sheep.

element	measurement	*n*	mean	min	max	SD	var.
astragalus (AST)	Bd	10	18.00	15.20	21.20	1.729	2.991
calcaneus (CAL)	GL	22	57.44	50.50	62.90	2.857	8.164
metacarpal (MC)	GL	19	131.32	120.50	141.00	6.704	44.949
	SD	19	13.99	11.15	16.20	1.217	1.480
	Bd	19	25.17	21.30	28.10	1.715	2.943
	Bp	20	22.77	19.70	25.00	1.450	2.103
metatarsal (MT)	GL	11	135.48	115.90	145.20	8.331	69.406
	SD	14	12.10	11.10	13.50	0.621	0.386
	Bd	13	22.71	21.03	24.80	1.156	1.336
	Bp	13	19.80	17.41	21.40	1.102	1.214
phalanx 1 (PH1)	Glpe	4	36.50	35.10	38.40	1.407	1.980
	SD	2	10.17	9.33	11.00	1.181	1.394
	Bd	2	10.40	8.00	12.80	3.394	11.520
	Bp	2	11.60	10.80	12.40	1.131	1.280
humerus (HUM)	Bd	48	30.39	27.00	35.00	2.076	4.310
radius (RAD)	GL	5	160.21	146.10	170.00	9.273	85.986
	Bd	25	29.44	24.00	33.00	2.375	5.638
	Bp	13	31.51	28.90	38.00	2.541	6.459
femur (FEM)	Bd	3	37.76	29.20	47.00	8.919	79.550
tibia (TIB)	Bd	53	26.87	21.74	44.80	3.748	14.045
	total *n*	317					

5.3 Comparative Sites

The following sites have been selected for comparative analysis based on specific criteria that ensure meaningful analytical strength when examining livestock morphology across temporal and spatial dimensions (Figure 5.1; Table 5.5). These criteria include: (1) chronological relevance, with sites spanning from the Viking Age

Figure 5.1. Skálholt and all comparative sites.

through the early modern period to enable temporal comparison; (2) adequate sample sizes, with sufficient measurable specimens to support statistical analysis; (3) standardized recording methodologies compatible with North Atlantic Biocultural Organization (NABO) protocols; (4) comprehensive documentation with secure context information; and (5) representation of diverse settlement types, from ordinary farms to specialized economic centers. This approach facilitates multi-scalar comparisons that situate Skálholt's faunal assemblage within increasingly broader frameworks: internally, between elite household areas and midden deposits; regionally, across Icelandic sites spanning different time periods and functions; and across the broader North Atlantic, incorporating data from Greenlandic settlements and contemporaneous British assemblages. Together, these sites create a comprehensive comparative framework for evaluating whether Skálholt represents continuity with traditional Icelandic practices or innovation potentially reflecting broader European agricultural currents during this critical period of transition.

5.3.1 Skálholt and Comparative Sites in Iceland

For the purposes of this research, two primary archaeological contexts within Skálholt provide the faunal material for examination: Midden Zone C, particularly context [454], which yielded exceptionally dense bone deposits near a documented meat storage facility; and interior spaces associated with the bishop's residence, referred to as "household" contexts. The comparative analysis of these distinct depositional contexts potentially offers insights into potential differences in consumption patterns between elite and service areas within this ecclesiastical complex. In another manifestation of Skálholt's distinctiveness, the rest of the Icelandic comparative sites are significantly further north (Figure 5.2).

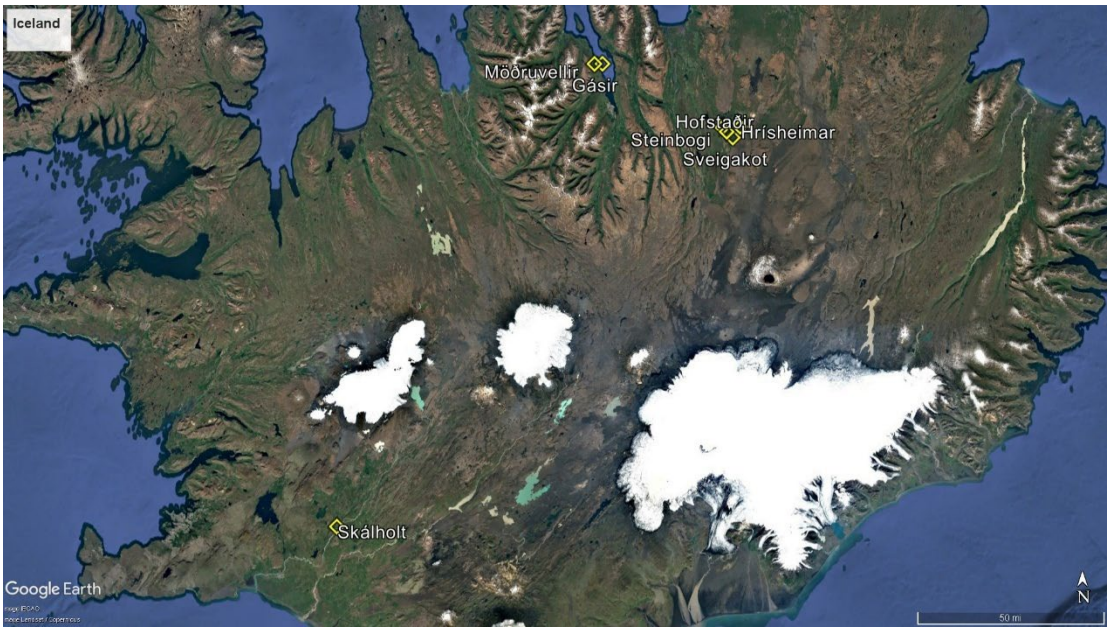

Figure 5.2. Skálholt and all comparative Icelandic sites.

Sveigakot

Sveigakot is located in the Mývatn region of northern Iceland, with midden deposits directly contacting the late ninth century *Landnám* tephra layer. Radiocarbon dating and tephrochronology indicate the site was occupied shortly after the deposition of the 871 ± 2 AD *Landnám* tephra and was entirely abandoned by the late twelfth century. Archaeological excavations have identified a small Viking Age longhouse approximately 12 meters long and 4 meters wide, along with a small pit house. The site's earliest settlement phase featured less substantial structures, primarily sunken-featured buildings, which were later replaced by the small hall (Vésteinsson et al. 2002).

The historical winter grazing area of the Sveigakot farm covers approximately 3.5 km² with an altitude ranging between 250 and 320 meters above sea level. This area is characterized by eroding and eroded aeolian sands on the Pleistocene Palagonite Formation, constrained by the river Kráka and the now barren 3800-year-old Laxárhraun lava (Cesario 2019). Environmental studies indicate that currently about 62% of the Sveigakot winter grazing area consists of bare ground – a proportion significantly higher than regional averages (Simpson et al. 2004). Soil profiles below the *Landnám* tephra show dark brown sandy silt loam and silt loam, while layers above typically consist of dark brown silt loams with weak soil structure. This evidence suggests an initially more promising landscape that has since deteriorated into an unstable, eroded state (Simpson et al. 2004).

Sveigakot is often compared with the nearby sites of Hofstaðir and Hrísheimar, all dating to the first phases of Norse occupation in the Mývatn district.

These comparisons reveal several distinctive patterns: Sveigakot showed lower percentages of migratory waterfowl, ptarmigan, and seabirds in its faunal remains compared to Hofstaðir and Hrísheimar. Notably, Sveigakot is located quite distant from present grebe habitat, potentially explaining some faunal differences (Thompson and Simpson 2007). The absence of bird eggshells at Sveigakot, contrasting with their presence at Hofstaðir and Hrísheimar, suggests possible differences in status and resource control between these sites. Based on structural and artifactual evidence, Sveigakot has been characterized as a probably poor tenant farm, while Hofstaðir represented a chieftain's manor farm and Hrísheimar a prosperous "iron farm" (McGovern et al. 2009).

The faunal assemblage from Sveigakot provides important comparative data for understanding early settlement period animal management practices in northern Iceland. While the structural characteristics suggest lower status, some aspects of the artifact and faunal assemblages exhibit characteristics typically associated with higher-status sites. The cattle to caprine ratio changed significantly over time, with cattle bone percentages declining from approximately 35% in the earliest deposits (c. 875-930 AD) to 20% in the eleventh century, suggesting shifting economic priorities or constraints as the settlement developed (McGovern et al. 2009).

Hrísheimar

Hrísheimar is an abandoned farm site located in the high-altitude Mývatn lake basin of northern Iceland, situated within the curve of a gravel ridge formed by a glacial esker deposit at an elevation of 310 meters above sea level. Positioned near

the headwaters of small streams that form Gautlandalaekur, flowing north to Arnarvatn and then the Laxá river, a still-extensive bog extends south and southwest of the site (McGovern et al. in press).

The chronology of Hrísheimar is securely established through tephrochronology and radiocarbon dating. The site was first occupied immediately after the fall of the *Landnám* tephra, with cultural deposits resting directly on this volcanic layer. Hrísheimar was probably abandoned by approximately 1020-1050 AD, and the Hekla 1104 tephra layer runs above the final observed occupational layers, confirming that Hrísheimar was exclusively a Viking Age site (McGovern et al. in press). Evidence suggests an early campground on the brush-covered hill slope immediately post-*Landnám*, followed by construction of multiple structures including at least two sunken feature structures and a substantial, well-constructed privy comparable to the one at Hofstaðir.

Significant finds include large collections of animal bone, artifacts, and bird eggshell. The site has yielded considerable evidence for iron production, with remains of iron smelters along the eroded ridge line north of the Viking Age deposits. Notable artifacts include elite items such as amber beads and a sword chape, alongside evidence of barley cultivation and, unusually in Iceland, oats (*Avena* sp.) (Bold and Church, in McGovern et al. in press). Archaeobotanical analysis revealed a general lack of driftwood, with birch and some willow serving as the primary fuel sources. The faunal assemblage indicates consumption of marine gadidae species from the early *Landnám* period, suggesting established trade connections despite the site's inland location.

Today, Hrísheimar is heavily eroded, with much of the original land surface lost to wind erosion. The site's abandonment by the mid-eleventh century despite its initial prosperity and abundant resources remains enigmatic, though extreme pressure on resources and potentially inappropriate management strategies have been suggested as contributing factors (Bold and Church, in McGovern et al. in press).

Hofstaðir

Hofstaðir is located in the Mývatn region of northern Iceland, specifically in the upper Laxá valley. The site lies approximately 10 kilometers from the sites of Hrísheimar and Sveigakot, positioned in what remains a prime trout fishing area along the Laxá river (Thompson and Simpson 2007). Archaeological excavations have revealed that Hofstaðir was a high-status Viking Age hall with associated buildings and midden deposits, occupied from approximately 940-1050 AD (Lucas 2009). The site has been subject to sustained landscape-scale multidisciplinary investigation, beginning initially as a single-site excavation before expanding into the broader Landscapes of Settlement project (McGovern et al. 2007).

The settlement's chronology is securely established through tephrochronology, with structures at Hofstaðir immediately postdating the *Landnám* tephra. While the location has been continuously occupied from initial settlement to the present day, the original settlement area was abandoned for an adjacent location before the fall of the Hekla tephra in 1104 AD. The Viking Age archaeofauna at Hofstaðir represents a relatively brief occupation span of approximately one century, potentially encompassing only three or four human generations (Lucas 2009).

Considered a chieftain's manor farm with some ritual functions, Hofstaðir likely held higher status than both the probable tenant farm at Sveigakot and the "iron farm" at Hrísheimar (McGovern et al. in press). The site's primary archaeological feature is a large hall-like structure exceeding 40 meters in length and 9 meters in width, accompanied by adjacent pit houses and associated artifacts. Excavations have targeted designated midden heaps and structural infill, with the largest midden deposit located outside the northwestern door of the aisled hall.

The faunal assemblage from Hofstaðir demonstrates strong continuity throughout the Viking Age occupation phases, suggesting stability in economic strategies (McGovern et al. 200. Notable aspects include a predominance of ptarmigan among wild species, though seabird remains are most concentrated at this site compared to contemporary settlements in the region. Hofstaðir, like other Mývatnssveit sites, provisioned its household with dried marine fish, showing a clear preference for flat dried cod and haddock over round dried products. This pattern indicates specialized marine connections despite the site's inland location (McGovern et al. 2009).

The site's domestic mammal assemblage has produced valuable biometrical data, with cattle remains showing morphological consistency with other North Atlantic Viking Age specimens: small stature, large-headed, short-horned, and stocky. Metacarpal measurements from sheep at Hofstaðir appear less robust than those from Sveigakot, suggesting potential differences in nourishment quality between sites despite Hofstaðir's higher status (Cussans 2010). Very little difference was observed in the majority of sheep bone measurements between the two sites, with

the exception of metacarpal morphology, offering a comparative dataset for examining husbandry practices and environmental adaptations across different settlement types (McGovern et al. 2009).

Steinbogi

Steinbogi is a small medieval farm site located in the Mývatn area of northern Iceland (Harrison 2009). Steinbogi's importance as a comparative site in the present work stems from its representation of smaller medieval farms within the settlement hierarchy. By providing contrast to sites like Gásir, Hofstaðir, and other higher-status establishments, the faunal assemblage from Steinbogi helps provide another view of economic and social organization in medieval Iceland. Faunal evidence suggests that Steinbogi maintained a subsistence strategy focused primarily on pastoral agriculture, with animal management practices reflective of its rural, inland location (Harrison 2009). This contrasting economic profile has been interpreted as evidence of different functional roles and varying degrees of connectivity to broader trade networks and ecclesiastical institutions such as Skálholt.

Gásir

Gásir functioned as a specialized seasonal trading center in the Eyjafjörður region of northern Iceland from the mid-thirteenth to early fifteenth centuries AD (Harrison and Roberts 2014). Located approximately 13 kilometers north of modern Akureyri, the site was strategically positioned in a coastal inlet at the southwestern end of a long fjord. Excavations conducted between 2001 and 2006 revealed an array

of booth-like sunken structures with associated trackways comprising the main trading area, alongside a church and churchyard that likely served visiting merchants (Harrison 2009).

Unlike typical Icelandic settlements, Gásir was neither a farm nor a fishing station but rather a specialized commercial node requiring external provisioning, often from the nearby ecclesiastical estate at Möðruvellir (Harrison 2007). The site exhibits clear evidence of specialized production zones for sulfur processing, bone and walrus ivory working, and fish processing, indicating its integration within broader trade networks (Harrison 2008, 2009). Excavations have yielded artifacts demonstrating international connections, including imported pottery and the remains of species such as gyrfalcons (*Falco rusitcolus*) and 'lap' dogs (*Canis familiaris*).

The site was provisioned with prime-aged cattle and sheep rather than the young calves or worn-out dairy cows characteristic of the period's dairying economy. The cattle/caprine ratio approached 2:1, resembling patterns observed at high-status late medieval sites in southern Iceland (Harrison 2009). Additionally, the presence of pig (*Sus scrofa*) remains – unusual for this period in Iceland – further distinguishes the assemblage (Harrison 2009, Harrison and Roberts 2014). This provisioning pattern, combined with evidence of luxury goods and high-status animals, suggests wealthy consumption practices and indicates strong connections to nearby estates such as Möðruvellir, which likely supplied much of Gásir's livestock (Harrison 2008).

Möðruvellir

Möðruvellir is situated in Hörgárdal, Eyjafjörður, northern Iceland, approximately 13 kilometers north of modern Akureyri. The site occupies open lowland pasture north of the river Hörgá, positioned near the river delta in a coastal environmental setting. Notably, Möðruvellir is located less than 5 kilometers west-southwest of Gásir, the medieval trading site with which it shared significant economic and provisioning relationships (Harrison 2007, 2008).

The site has maintained considerable importance throughout Icelandic history, with documentary evidence indicating the presence of a church from at least the mid-twelfth century. Toward the late thirteenth century, Möðruvellir was established as a House of Canons, signifying its elevated religious status (Vésteinsson 2001). These ecclesiastical activities were supported by produce from an extensive agricultural estate. Archaeological investigations have focused primarily on midden deposits from the sixteenth to eighteenth centuries, though evidence suggests much earlier activity at the site. A pagan burial mound (*kuml*) unearthed in the nineteenth century indicates settlement or mortuary activity predating 1000 AD, and there is evidence suggesting that one of the area's oldest farms, Akrar, was located on Möðruvellir grounds (Harrison and Roberts 2014; Vésteinsson 2001). The substantial farm mound, approximately 80 meters in diameter and rising 4-5 meters above the surrounding landscape, has yielded complex sequences of midden deposits with numerous artifacts and exceptionally well-preserved faunal remains, including rare organic materials such as wood and cloth (Harrison 2007, 2008).

5.3.2 Comparative Sites Across the North Atlantic

Western Settlement, Greenland

The Western Settlement was one of two main areas colonized by Norse settlers in Greenland, located further north than the Eastern Settlement in the area around present-day Nuuk (Godthåb) and consists primarily of farm sites with associated middens (Figure 5.3; Banks 1975). Archaeological research has identified a hierarchical settlement structure with secondary, tertiary, and quaternary sites represented, while the highest-status primary sites may have been located in the Eastern Settlement (McGovern 1985).

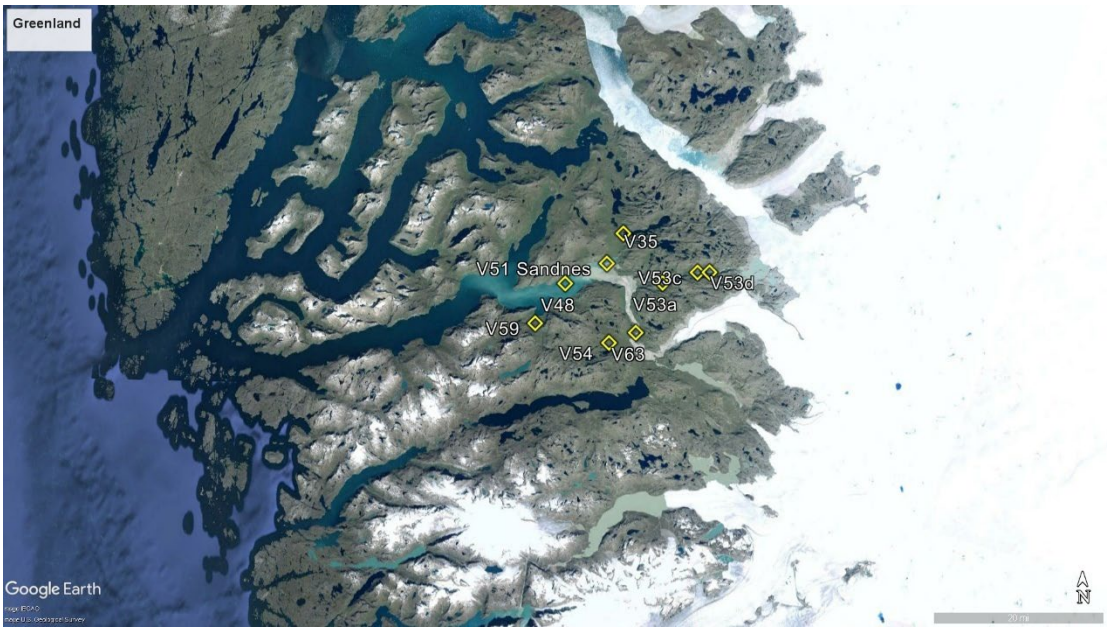

Figure 5.3. Comparative sites in the Western Settlement - Greenland.

Settlement began around AD 982 when Erik the Red and his followers arrived from Iceland (Arneborg 2000). The landscape at the time of Norse arrival likely consisted of dense alder scrub, penetrable mainly along caribou trails. Historical

sources indicate the Western Settlement was abandoned around 1360, though archaeological evidence suggests some farms, like Gården under Sandet (GUS), may have been occupied until the fifteenth century (Arneborg 2003; Cussans 2017; McGovern et al. 1996, 2014). The abandonment likely resulted from multiple factors, including climate change, erosion, limited adaptation compared to the Inuit, decreased demand for trade goods, and potentially poor political decisions (McGovern 2000).

The faunal assemblages from Western Settlement sites exhibit distinctive characteristics compared to other Norse North Atlantic settlements. Dogs and caprines (sheep and goat) were more abundant than in the Eastern Settlement, while cattle, horse (*Equus* sp.), and pig remains were less common. Wild resources, particularly harp seals (*Pagophilus groenlandicus*), common seals (*Phoca vitulina*), walrus (*Odobenus rosmarus*), shellfish (Mollusca), and caribou (*Rangifer tarandus*) feature prominently in the assemblages (McGovern 1985). Zooarchaeological analysis indicates that Greenlandic cattle were largely used for dairying, while caprines served mixed purposes of meat and secondary products (Arneborg et al. 2012). Stable isotope data shows an increased marine component in the Norse Greenlandic diet over time, from approximately 20% early in settlement to 80% toward the end (Arneborg et al. 1999). V51 (Sandnes) represented the highest status site identified in the Western Settlement, a church farm occupied during the later settlement period (fourteenth-fifteenth century) (Arneborg et al. 2012). The Western Settlement material provides valuable comparative data for understanding livestock adaptation under severe environmental constraints at the northernmost extent of

medieval European agriculture, though in this present work, the Western Settlement biometrical data does not include Gården under Sandet (GUS).

Old Scatness, Shetland

Old Scatness is a multi-period settlement located in the south mainland of Shetland, Scotland (Figure 5.4; Dockrill 2013). The site is principally focused on a broch (circular stone tower) and the surrounding Iron Age occupation, though archaeological evidence demonstrates continuous occupation spanning from the Neolithic period through to the nineteenth century (Outram et al. 2010).

Figure 5.4. Old Scatness, Shetland.

Excavations at Old Scatness involved detailed sampling and recording protocols, resulting in the recovery of large quantities of biological remains that provide extensive evidence for the site's economy and environment. The

chronological sequence at Old Scatness has been divided into eleven phases, from the Neolithic to the eighteenth-century crofting period (Cussans 2010). Bone metrical data is available in varying quantities for all phases from Phase 4 (the Broch period) onwards, though the comparative data used in this study are only from Phases 10 (post-medieval, seventeenth and eighteenth centuries) and 11 (crofting period, eighteenth century).

The faunal assemblage from Old Scatness provides important evidence for continuity and change in livestock management practices in the Northern Isles. There is evidence suggesting increased emphasis on sheep husbandry over time, potentially indicating agricultural intensification (Cussans 2010). For the contexts included in this current research, the faunal assemblage is entirely sheep, with no cattle present. Regarding the broader environment of Shetland, Bennett and colleagues (1992) concluded that after the initial removal of woodland, the vegetation cover and land-use within the islands showed relatively little variation over the past 3,000 years. This suggests a stable landscape from the Bronze Age onwards, encompassing the main periods of occupation at Old Scatness. The site thus provides an important reference point for understanding livestock development in a relatively stable insular environment, in contrast to the more dramatic landscape changes documented in Iceland following Norse settlement.

The Shires, Leicester, England

The Shires is an urban archaeological site located in the city center of Leicester, Leicestershire, England, encompassing two main excavation areas: Little

Lane and St. Peter's Lane. These sites were excavated from 1988-1989 in what is now known as the Highcross district (Figure 5.5; Lucas and Buckley 2007). While the site's chronology extends from Roman to modern periods, this analysis focuses specifically on the medieval and early post-medieval contexts dating from the fourteenth to the seventeenth centuries, which provide valuable comparative material for examining changes in animal husbandry practices within an urban setting in central England (Grau-Sologestoa and Albarella 2019).

Figure 5.5. The Shires, Leicester City Centre, England.

The faunal assemblage from The Shires was initially studied by L.J. Gidney, with findings documented in several English Heritage Ancient Monuments Laboratory Reports (1991a, b, c, 1992, 1993). More recently, Grau-Sologestoa and Albarella (2019) re-analyzed the material from the late medieval and early post-medieval contexts, focusing specifically on identifying the timing and nature of

animal husbandry changes during what is termed the “long” sixteenth century (approximately 1450-1650 AD).

The faunal evidence from The Shires conforms to patterns observed at other central English sites, indicating that cattle remained more prevalent than sheep throughout both medieval and post-medieval periods (Holmes 2014, 2018). A notable shift in husbandry practices is evidenced by increased calf slaughter in the latest medieval and post-medieval periods, suggesting a growing emphasis on veal and dairy production. This pattern aligns with broader changes in English agriculture during this period, often associated with the early phases of agricultural improvement that ultimately led to the more formalized Agricultural Revolution of the eighteenth century (Thomas 2005; Thomas et al. 2013; see discussion on the Second Agricultural Revolution in Chapter 4)

The urban context of The Shires provides an important comparative framework for understanding how livestock morphology changed in response to emerging market pressures and agricultural intensification. Unlike the relatively isolated North Atlantic settlements, Leicester maintained extensive connections to surrounding rural hinterlands and participated in broader regional and national economic networks of England and beyond into continental Europe (Grau-Sologestoa and Albarella 2019). The faunal assemblage from The Shires thus offers valuable insights into livestock morphology during a transformative period in English agricultural history. By comparing these materials with roughly contemporaneous assemblages from Iceland, we can examine how similar chronological processes manifested differently across distinct environmental, economic, and cultural contexts.

Table 5.5. Counts and means of length and width dimensions by site and taxon.

Omitted dimensions have insufficient sample size (>10)

site	species	dimension	*n*	mean
Sveigakot	*Ovis*	length	70	0.020
		width	142	0.008
	Bos	length	11	-0.008
		width	19	0.050
Hrísheimar	*Ovis*	length	31	0.011
		width	93	0.014
	Bos	length	13	-0.018
		width	25	0.012
Hofstaðir	*Ovis*	length	74	0.018
		width	157	0.005
	Bos	width	18	0.023
Steinbogi	*Ovis*	width	58	0.011
Gásir	*Ovis*	length	21	0.067
		width	89	0.057
	Bos	width	27	-0.001
Möðruvellir	*Ovis*	width	26	0.038
Skálholt	*Ovis*	length	63	0.033
		width	188	0.019
	Bos	length	10	-0.060
	Bos	width	88	0.004
Western Settlement	*Ovis*	length	51	-0.003
		width	179	0.013
	Bos	length	51	-0.025
		width	64	0.031
Old Scatness	*Ovis*	length	49	0.0001
		width	104	0.012
The Shires	*Bos*	length	24	0.020
		width	108	0.044

5.4 Data Processing

All statistical analyses were conducted using R version 4.4.2 (R Core Team 2024) and RStudio version 2024.12.0 (RStudio Team 2024). Log ratios calculation and analysis was undertaken using the package *zoolog* for R (Pozo et al. 2023). Log-ratio values were calculated using the following equation:

$$log\text{-}ratio = log_{10}(archaeological\ specimen/standard\ measurement)$$

A log-ratio value of zero indicates that the archaeological measurement is equal to the reference standard. Positive log-ratio values denote archaeological measurements that are larger than the reference, while negative values signify that the archaeological specimen is smaller than the reference standard. The reference standards chosen for this analysis include a set of mean measurements of adult male Soay sheep from a single flock from Hirta, St. Kilda, Scotland (n = 71, Clutton-Brock et al. 1990) and a set of measurements of a Bronze Age cow from Catalonia, Spain (n = 68, Nieto-Espinet 2018).

The Soay standard provides particular analytical utility for North Atlantic assemblages given the breed's status as a primitive northern short-tailed morphotype ("breed") with potential morphological similarities to medieval Icelandic sheep (Ryder 1983; Adalsteinsson 1990). While the Bronze Age cow standard represents a chronologically earlier specimen, it offers comprehensive measurement coverage across skeletal elements that facilitates standardized comparative analysis (Nieto-Espinet 2018).

Table 5.6. Standard measurements used for the calculation of log-ratio values for cattle and sheep. Measurement dimensions follow von den Driesch 1976, the Bos *values are from a Bronze Age cow (Catalonia; Nieto-Espinet 2018), and the* Ovis *values are from modern Soay sheep (St. Kilda; Clutton-Brock et al. 1990). Values for phalanx 1 from both standards represent anterior elements from the forelimb.*

element	measurement	***Bos*** **value (mm) (Nieto-Espinet 2018)**	***Ovis*** **value (mm) (Clutton-Brock et al. 1990)**
astragalus (AST)	Bd	39.00	17.21
calcaneus (CAL)	GL	123.00	52.20
metacarpal (MC)	GL	176.00	119.93
	SD	24.00	14.10
	Bd	47.30	23.70
	Bp	45.30	21.74
metatarsal (MT)	GL	208.00	128.66
	SD	22.40	11.87
	Bd	45.00	22.63
	Bp	38.70	19.01
phalanx 1 (PH1)	Glpe	56.00	34.74
	SD	23.00	9.77
	Bd	26.00	11.05
	Bp	28.00	11.90
humerus (HUM)	Bd	74.90	28.62
radius (RAD)	GL	248.20	142.40
	Bd	69.70	27.64
	Bp	72.90	29.70
femur (FEM)	Bd	85.00	36.88
tibia (TIB)	Bd	55.20	24.75

One length and one width log-ratio value from each specimen were included in the analysis, with values selected following the default *zoolog* 'priority' method (Trentacoste et al. 2018): length values - GL; width values - Bd, Bp, SD. This approach ensures that only one length and one width log-ratio value, chosen based on a hierarchy of measurement reliability, are included for each bone specimen and works to avoid potential overrepresentation of specimens with multiple measurements and statistical biases due to correlated values (Pozo et al. 2023). The reference$combi

database within *zoolog* provided standardized measurement values for the comprehensive suite of skeletal elements analyzed in this study (Table 5.6).

Prior to conducting statistical analyses, data were tested for normality using the Shapiro-Wilk test (Shapiro and Wilk 1965) and homogeneity of variances using Levene's test (Levene 1960). When assumptions of normality and homogeneity of variance were met, one-way analysis of variance (ANOVA) was conducted to assess differences between sample populations of taxa, of elements, or of biometrical dimensions (Fisher 1925). Post-hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test to control for family-wise error rate (Tukey 1949). In cases where data violated assumptions of normality or homogeneity of variance, the non-parametric Kruskal-Wallis test was used as an alternative to ANOVA (Kruskal and Wallis 1952), followed by pairwise Wilcoxon rank-sum tests with Bonferroni correction for multiple comparisons (Wilcoxon 1992). Statistical significance was set at $\alpha = 0.05$ for all analyses.

For datasets requiring more nuanced pairwise comparisons after a significant Kruskal-Wallis result, Dunn's test (Dunn 1964) was implemented for non-parametric multiple comparisons. This test is particularly appropriate for comparing groups with unequal sample sizes – a common challenge in zooarchaeological assemblages. Unlike some alternative post-hoc methods, Dunn's test does not assume equal variances or similar distributions across groups, making it well-suited for archaeological datasets where preservation biases and recovery methods often produce heterogeneous samples (Zar 2014). The test converts ranks from the Kruskal-Wallis procedure into z-scores for each pairwise comparison and calculates p-values

based on these scores. To control for Type I errors resulting from multiple comparisons, p-values were adjusted using the Benjamini-Hochberg procedure, which provides better statistical power than the more conservative Bonferroni method while still controlling the false discovery rate (Benjamini and Hochberg 1995). Dunn's test was implemented in R using the *dunn.test* package (Dinno 2017).

Pearson's product-moment correlation coefficient (Pearson's *r*) was used to measure the strength and direction of linear relationships between pairs of continuous variables (Lee Rodgers and Nicewander 1988). The coefficient ranges from -1 to +1, with values closer to -1 indicating a strong negative correlation, values closer to +1 indicating a strong positive correlation, and values near 0 indicating a weak or non-linear relationship. The statistical significance of correlation coefficients was determined using a two-tailed t-test, with the null hypothesis being that the population correlation coefficient is equal to zero (Fisher 1915). Scatterplots were inspected to ensure that relationships between variables were linear and to identify any outliers that could strongly influence the correlation coefficient. In cases where relationships between variables were non-linear or where outliers were present, the non-parametric Spearman's rank correlation coefficient (Spearman's ρ) was used as a more robust alternative to Pearson's r (Zar 2014). Statistical significance was set at $\alpha = 0.05$ for all correlations.

Hartigan's dip test was employed to assess potential bimodality in withers height distributions (Hartigan and Hartigan 1985). This non-parametric statistical test evaluates the null hypothesis that a sample is drawn from a unimodal distribution. The test quantifies the maximum difference between the empirical distribution

function and the unimodal distribution function that minimizes this maximum difference. A significant p-value (typically $p < 0.05$) indicates evidence against unimodality, suggesting that the distribution might be multimodal. For distributions showing potential bimodality, mixture analysis was subsequently performed to identify potential component distributions and their relative proportions.

Several measures were taken to ensure data reliability and address potential measurement or recording errors. During initial data assessment, measurements were examined for consistency and plausibility. Potential outliers were identified using both statistical methods (z-scores exceeding ±3) and visual inspection of boxplots and histograms. Rather than implementing automatic outlier removal based solely on statistical thresholds, each potential outlier was evaluated individually to determine whether it represented a genuine biological signal or a potential error.

Within the Skálholt sheep assemblage, a small number of statistical outliers ($n = 4$) were omitted from the analysis to ensure the robustness of the results. These included two tibia (TIB) measurements with log-ratio values of 0.253 and 0.261, which exceeded three standard deviations from the mean. Additionally, one duplicate tibia measurement (log-ratio value 0.175) was removed to prevent double-counting of the same specimen. These exclusions were deemed necessary to maintain statistical integrity and prevent potential recording errors from distorting the analytical results.

The uneven distribution of measurements across different elements and the relative scarcity of length measurements compared to width measurements represent inherent limitations in the dataset. This disparity is particularly pronounced for cattle from Skálholt and sheep from Möðruvellir and Steinbogi. While this imbalance

reflects common preservation patterns in archaeological assemblages, it necessarily constrains certain analytical approaches, particularly those requiring paired length and width measurements from the same specimens.

5.4.1 Withers Height Determination

The reconstruction of livestock stature (withers height) provides valuable dimensional data that complements log-ratio analysis by offering intuitive size measurements that facilitate both cross-site comparisons and broader contextual interpretations (Albarella 1997a, 2002). For the Skálholt assemblage, withers height was reconstructed primarily from intact metapodials and radii following established methodologies appropriate to each taxon.

For sheep, withers height was calculated using Teichert's (1975) factors, which provide multiplication coefficients for various long bones. When these coefficients are applied to the greatest length (GL) of specific skeletal elements, they yield estimates of the animal's standing height at the withers. The metapodials (metacarpals and metatarsals) and radii provide particularly reliable estimations due to their relatively standardized proportional relationship to overall height across different sheep breeds (Davis 2000; Thomas et al. 2013).

For cattle, factors developed by von den Driesch and Boessneck (1974) were employed, with sex-specific coefficients applied where possible (Table 5.7). The sexual dimorphism in cattle skeletal proportions necessitates different multiplication factors for males, females, and castrates, particularly for metapodial elements (Thomas et al. 2013; Wright and Viner-Daniels 2015).

Table 5.7. Withers height multiplication factors (sheep - Teichert 1975; cattle - von den Driesch and Boessneck 1974).

species	element	multiplication factor
sheep	metacarpal	GL*4.89
	metatarsal	GL*4.54
	radius	GL*4.02
cattle	metacarpal	GL*6.18 (females)
		GL*6.25 (males & castrates)
	metatarsal	GL*5.47 (females)
		GL*5.45 (males & castrates)

When sex determination was possible for cattle specimens, the appropriate coefficient was applied. In cases where sex could not be reliably determined, both calculations were performed to establish a potential range of values. This approach acknowledges the sexual dimorphism in cattle while maximizing the interpretive value of available specimens.

While withers height calculations provide valuable dimensional insights, several factors must be considered when interpreting these measurements in archaeological contexts. The multiplication factors were developed from specific reference populations that may differ morphologically from medieval and post-medieval Icelandic livestock (Albarella 2002; Zeder 2006). Additionally, taphonomic processes affecting bone preservation and measurement accuracy introduce further variables (Reitz and Wing 2008). Consequently, the calculated heights should be understood as estimates rather than precise measurements, most valuable for comparative analysis across similar assemblages rather than absolute determinations of stature (Albarella 1997a; Thomas et al. 2013).

5.4.2 Wether Identification Methods

The identification of castrated males (wethers in sheep; steers in cattle) represents a crucial dimension of livestock management reconstruction with significant implications for interpreting production strategies in early modern Iceland. Castrates typically develop distinctive skeletal characteristics that can be identified through systematic biometrical analysis, though these patterns often overlap with both male and female morphological ranges, creating interpretive challenges (Davis 2000; Popkin et al. 2012; Thomas et al. 2013).

For the Skálholt assemblage, wether identification focused primarily on analyzing long bone proportions, particularly the relationship between length and width dimensions in metapodials. Following methodologies established by Davis (2000), Hatting (1983), and further refined by Popkin and colleagues (2012), castrates were identified based on their tendency to develop longer but more slender long bones compared to intact males. This distinctive pattern results from delayed epiphyseal fusion in castrates, allowing extended longitudinal growth while simultaneously producing reduced shaft thickness due to altered hormonal influence on bone development (Davis and Beckett 1999; Hatting 1983).

Metapodials provide particularly valuable elements for distinguishing between females, intact males, and castrates due to their distinctive responses to sex-specific hormonal influences and their relatively abundant preservation in archaeological contexts (Davis 2000; Thomas et al. 2013). Three primary measurements were employed in this analysis:

- Greatest length (GL) - reflecting overall bone length influenced by growth duration
- Smallest shaft diameter (SD) - indicating robusticity influenced by hormonal factors
- Distal breadth (Bd) - providing additional dimensional data on epiphyseal development

Following the approach developed by Davis (2000) and further refined by Popkin et al. (2012), scatter plots of GL versus SD were created to visualize the distribution of specimens. In these plots, intact males typically cluster in the upper right quadrant (high GL, high SD), females in the lower left quadrant (low GL, low SD), and castrates in the upper left quadrant (high GL, low SD). This distinctive triangular distribution pattern, when present, provides strong evidence for wether presence in an assemblage (Davis 2000; Popkin et al. 2012).

Additionally, slenderness indices (SD/GL × 100) were calculated for each specimen to quantify the relationship between shaft diameter and length (Guintard and Lallemand 2003). Lower values, indicating more slender bones relative to their length, suggest possible castrate status. These indices were compared with reference data from Davis (2000) on modern Shetland sheep of known sex and castration status to establish appropriate thresholds for identification. For cattle, similar principles apply, though the effects of castration often manifest differently due to the greater sexual dimorphism in bovines (Howard 1963; Thomas et al. 2013).

Several factors complicate the reliable identification of castrates in archaeological assemblages. The effects of castration on skeletal development vary depending on the age at which castration occurred, with earlier castration producing

more pronounced effects (Davis 2000; Hatting 1983). Environmental and nutritional factors can influence bone proportions in ways that partially mimic or mask castration effects, potentially leading to misidentification (Popkin et al. 2012; Zeder and Lemoine 2020). Furthermore, breed differences create baseline variation that must be considered when applying reference standards derived from specific modern breeds like Shetland sheep (Albarella 2002; Davis 2000).

Given these complexities, this analysis employs a population-level approach rather than attempting definitive classification of individual specimens. By examining the overall distribution patterns within the assemblage and comparing them with established reference data, we can identify probable demographic compositions that include wethers, while acknowledging the inherent uncertainty in individual specimen identification. These patterns are then interpreted in relation to historical evidence for livestock management practices at Skálholt and comparative data from contemporaneous sites, providing a more robust foundation for understanding specialized animal management strategies at this elite ecclesiastical center.

5.5 Summary

The methodological approaches outlined in this chapter establish a framework for analyzing faunal remains from Skálholt and situating them within the broader North Atlantic context. The integration of multiple analytical techniques – biometrical analysis through log-ratio scaling, withers height estimation, slenderness indices analysis, and wether identification methods – constructs a multidimensional foundation for addressing questions about livestock improvement, environmental

adaptation, and socioeconomic influences on animal management practices in early modern Iceland.

This research addresses several methodological challenges inherent to zooarchaeological investigations. The differential preservation of skeletal elements creates systematic biases in the available measurements, with length measurements consistently underrepresented relative to width measurements across all assemblages. This preservation pattern, particularly evident in the scarcity of complete long bones suitable for withers height reconstruction, necessitates careful interpretive approaches when examining morphological patterns potentially indicative of castration or selective breeding. Similarly, the uneven sample sizes across sites, contexts, and chronological periods requires appropriate statistical methodologies to ensure valid comparisons without overextending interpretations beyond what the data can reliably support.

The statistical methods employed balance analytical rigor with the realities of archaeological data. Non-parametric approaches (Kruskal-Wallis, Wilcoxon rank-sum tests) were deployed when data violated assumptions of normality or homogeneity of variance, while parametric methods (ANOVA, Tukey's HSD) were applied when appropriate. Dunn's test with Benjamini-Hochberg correction provided particularly valuable insights when comparing groups with unequal sample sizes – a common challenge in zooarchaeological assemblages. This methodological flexibility, combined with systematic data screening and outlier assessment, enhances the reliability of comparative analyses while acknowledging the inherent limitations of archaeological materials.

The multiscalar comparative framework situates Skálholt's assemblage within progressively broader contexts: from internal spatial organization to regional patterns to North Atlantic-wide comparisons. This approach reveals how morphological patterns reflect not only site-specific practices but also broader regional adaptations, cultural traditions, and economic networks. By examining biometrical data across these nested scales, we can distinguish localized management strategies from broader currents of agricultural change during this transitional period.

The methodological framework established here builds upon established protocols in North Atlantic zooarchaeology while incorporating innovations in statistical analysis and comparative techniques. The standardized approach to measurement, recording, and analysis ensures comparability with both previous and future research, contributing to ongoing efforts to understand the complex interplay between human societies, livestock management, and environmental conditions across the North Atlantic world. By situating Skálholt's faunal assemblage within multiple comparative contexts, from internal spatial organization to broader regional patterns, this approach illuminates how this elite ecclesiastical center navigated the challenging environmental conditions of early modern Iceland while potentially implementing innovative management practices that distinguished it from ordinary farms of the period.

Chapter 6: Results

This chapter presents the results of biometrical analysis conducted on postcranial faunal remains from Skálholt, an elite ecclesiastical center in southern Iceland, occupied from the eleventh through eighteenth centuries. The analysis focuses on cattle (*Bos taurus*) and sheep (*Ovis aries*) remains dated to the seventeenth and eighteenth centuries, a period coinciding with significant agricultural transitions across Europe. By examining morphological characteristics through log-ratio scaling techniques, this research addresses fundamental questions about livestock improvement, environmental adaptation, and the influence of elite status on animal management practices in early modern Iceland.

The comparative framework situates Skálholt's faunal assemblage within three nested contexts: internally, between elite household areas and midden deposits; regionally, in relation to other Icelandic sites spanning the settlement period (*Landnám*) through the post-medieval period; and across the broader North Atlantic, incorporating data from Greenlandic settlements and contemporaneous British assemblages. This multi-scalar approach enables examination of how livestock morphology at Skálholt reflected broader patterns of agricultural change, particularly in relation to developments associated with England's "long" sixteenth century and the early phases of the Second Agricultural Revolution.

For cattle, the analysis explores whether Skálholt's assemblage demonstrates evidence of specialized beef production that would distinguish it from the predominantly dairy-focused economy typical of early modern Iceland. Dimensional analysis of key elements, including metapodials, limb bones, and phalanges, offers

insights into potential castration practices, specialized breeding, and management strategies that might reflect elite economic priorities and continental European connections.

For sheep, the analysis examines morphological evidence for potential breeding improvements, specialized wool production through wether (castrated male) management, and adaptive responses to Iceland's challenging environmental conditions. By analyzing proportional relationships between length and width dimensions across multiple skeletal elements, this study investigates whether Skálholt's sheep assemblage shows distinctive characteristics that might indicate engagement with emerging European agricultural improvement concepts.

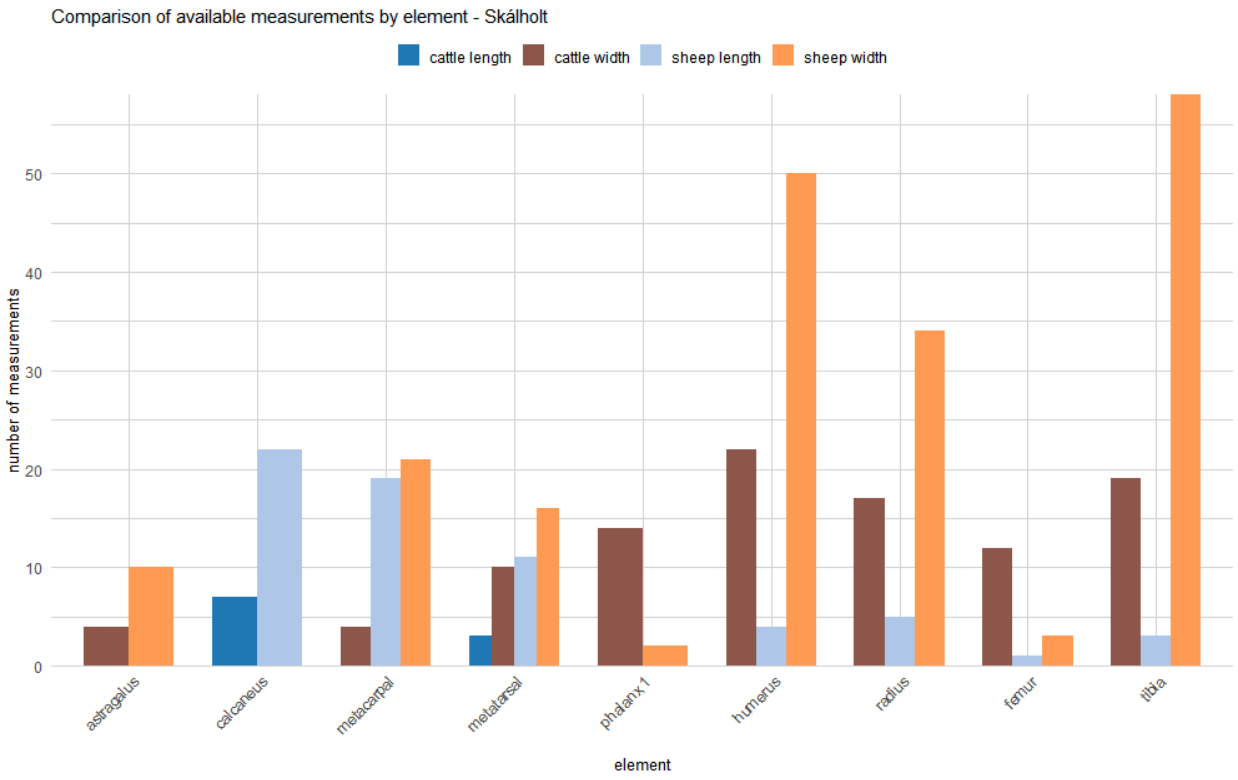

Figure 6.1. Comparison of available measurements by element (Bos taurus and Ovis aries) – Skálholt.

Figure 6.1 illustrates the distribution of available post-cranial measurements by element for both cattle and sheep at Skálholt. This distribution reflects both taphonomic patterns and recovery methodologies, with some elements significantly better represented than others. For cattle, the most numerous measurements derive from the humerus, radius, femur, and tibia, providing a dataset for analyzing limb bone morphology. The relatively high number of phalanx 1 measurements (n = 14) requires some interpretive caution, as these predominantly derive from Household contexts (n = 11) rather than Midden Zone C, which supplies most other cattle elements. This contextual difference will be addressed specifically in a subsequent section of this chapter.

For sheep, the measurement distribution shows a particularly strong representation of tibia, humerus, and radius widths, complemented by substantial length measurements for calcanei and metapodials. This complementary distribution of different measurement types across various elements enhances our ability to examine relationships between length and width dimensions – a crucial factor for identifying potential wether presence and specialized herding strategies.

By integrating these varied analytical approaches, this chapter explores how Skálholt's elite status may have influenced livestock management practices during a period of significant agricultural transition across Europe. The results provide insights into both localized adaptations to Iceland's distinctive environmental constraints and potential participation in broader European currents of agricultural innovation during the early modern period.

6.1 Cattle

The biometrical analysis of cattle remains from Skálholt provides valuable insights into livestock management practices at this elite ecclesiastical center during the early modern period. This section examines the morphological characteristics of cattle bones through log-ratio scaling techniques, comparing the Skálholt assemblage with other Icelandic sites and broader North Atlantic contexts. The analysis focuses particularly on identifying evidence for specialized husbandry practices, potential breed improvement efforts, and distinctive consumption patterns that might reflect Skálholt's elite status and ecclesiastical function.

The cattle assemblage from Skálholt has previously been noted for its distinctive characteristics, including unusually high percentages of cattle elements compared to typical Icelandic sites of the period and evidence of specialized breeding practices such as artificial polling (Hambrecht 2011, 2012). The current biometrical analysis extends this work by systematically examining dimensional patterns across multiple skeletal elements to address specific questions about beef production, breeding strategies, and potential engagement with broader European agricultural improvement movements. By situating these patterns within comparative frameworks across both time and space, we can evaluate whether Skálholt's cattle management represents continuity with traditional Icelandic practices or innovative adaptations potentially reflecting continental European influences.

6.1.1 The Skálholt Cattle

The biometrical data for Skálholt's cattle assemblage yielded 97 length and width measurements suitable for log-ratio analysis: nine length measurements and 88 width measurements (Figure 2), compared against a reference standard from a Bronze Age cow from Catalonia, Spain (n = 68, Nieto-Espinet 2018). Unfortunately, due to the limited number of length measurements and their uneven distribution across contexts, these were excluded from further consideration. This thus restricts the focus of this analysis of Skálholt's cattle to the log-scaled width dimension.

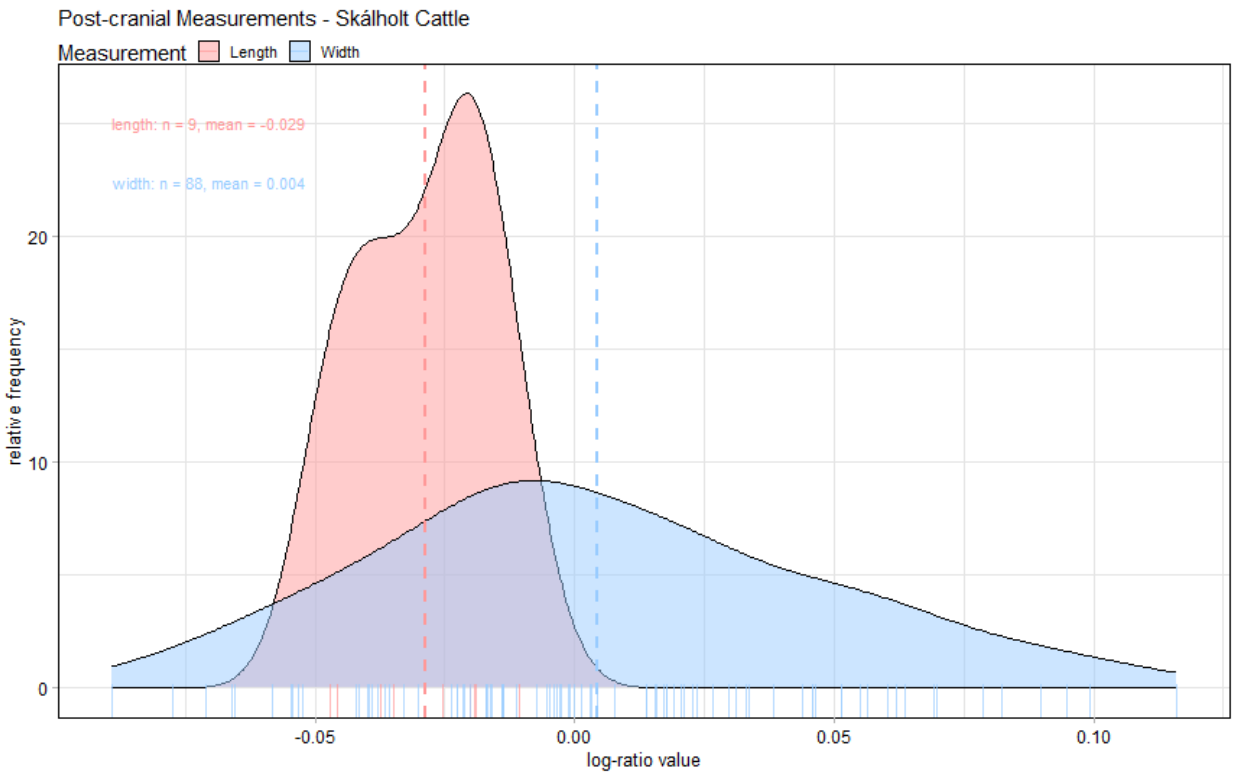

Figure 6.2. Post-cranial log-ratio measurements of Skálholt cattle by dimension. Length n = *9, mean = -0.029. Width* n = *88, mean = 0.004. Lengths are excluded from further analysis. "Relatively frequency" is expressed as a percentage of total number of data points that fall within a specific bin.*

Table 6.1. Number of Length and Width log-ratio values for all Skálholt cattle by element.

element	*n* length	*n* width
astragalus	0	4
calcaneus	6	0
metacarpal	0	4
metatarsal	3	10
phalanx 1	0	14
humerus	0	22
radius	0	17
femur	0	12
tibia	0	19
total *n*	9	102

The width data themselves in Skálholt's cattle assemblage are primarily comprised of material from Midden Zone C and represents a relatively substantial collection of measurable postcranial elements from exceptionally well-preserved bone deposits found outside the central complex (Tables 6.1 and 6.2). Log-scaled measurements from Midden Zone C are almost entirely dated to Phase M.1: between 1650 and 1700 AD (Lucas and Snæsdóttir 2022:175). While biometrical analysis of the sheep remains allow for a bifurcated view into the Household at Skálholt versus Midden Zone C, only two width measurements (mean = 0.034) are present for cattle within Household contexts.

Table 6.2. Width measurements for Skálholt cattle in Midden Zone C by element.

element	***n***
astragalus	3
calcaneus	0
metacarpal	4
metatarsal	7
phalanx 1	0
humerus	18
radius	14
femur	12
tibia	18
total *n*	76

These deposits formed where multiple dumps of refuse, ash, and fill accumulated on a sloping knoll near one of the entrances to the complex and a meat storage shed where butchery likely occurred (Hambrecht 2011). While the analyzed sample size from this midden ($n = 76$) is relatively modest by some standards, it represents one of the larger measurable assemblages from Iceland or indeed much of the contemporary North Atlantic, where preservation conditions and recovery contexts often limit the availability of complete measurable elements. The midden appears to represent both domestic consumption and butchery waste, with bone elements from across the skeleton and evidence of various stages of carcass processing. The mean log-ratio value of 0.005 for cattle width measurements suggests animals of generally comparable size to the reference standard (Figure 6.3).

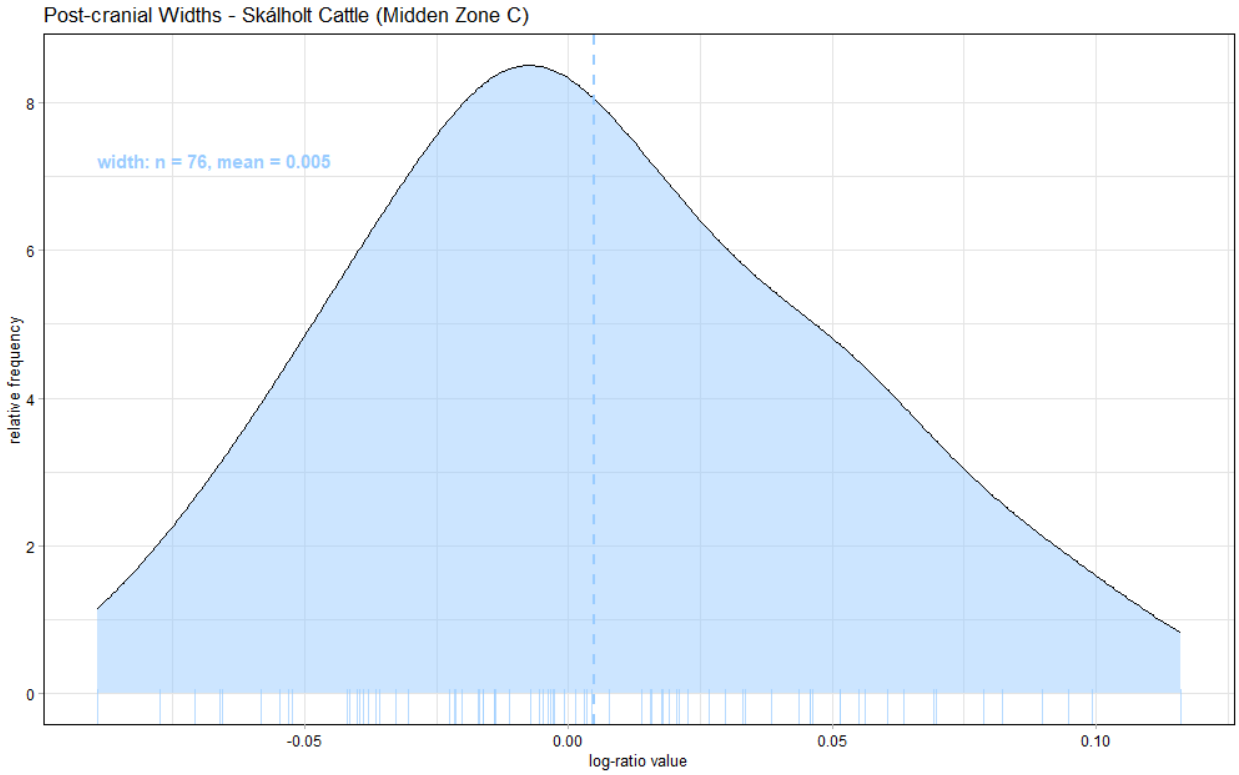

Figure 6.3. Post-cranial log-ratio width measurements of Skálholt cattle - Midden Zone C. Width n = *76, mean = 0.005.*

The lack of a robust sample size of log-ratio length measurements in the Skálholt cattle assemblage introduces constraints on our interpretative possibilities. This limitation is particularly relevant when attempting to identify the presence of oxen or castrates in the population, as these animals typically exhibit greater increases in bone length than width due to delayed epiphyseal fusion. While width measurements can be useful indicators of sexual dimorphism - with bulls generally showing broader bones than cows, particularly in metapodials - the absence of corresponding length measurements prevents the exploration of the more nuanced morphological signatures that might distinguish between intact males, females, and castrates (Grau-Sologestoa et al. 2021). For instance, castrates typically develop

longer but more slender bones compared to bulls, a pattern that requires both length and width measurements to identify. Likewise, broader metacarpal measurements might suggest the presence of bulls (Grigson 1982).

First Phalanges in Skálholt Cattle. The cattle first phalanges (phalanx 1) from Skálholt are presented separately from the rest of the assemblage because unlike other skeletal elements analyzed in this study, which predominantly derive from Midden Zone C contexts, the majority of phalanx 1 width measurements (n = 11 of 14) originate from Household contexts, specifically the storeroom adjacent to bishop's dining area. This contextual segregation creates interpretive challenges when attempting to integrate phalanx 1 data with the wider cattle measurement dataset. The density curve distribution for these measurements illustrates a relatively tight clustering with minimal variation, suggesting a potentially homogeneous source population (Figure 6.4).

When comparing Skálholt phalanx 1 width measurements with those from earlier sites like Sveigakot and Hofstaðir, several notable patterns emerge (Figure 6.5). The Skálholt distribution shows a narrower, more peaked curve centered slightly below zero, indicating relatively consistent dimensions that are marginally smaller than the reference standard. In contrast, the Sveigakot distribution demonstrates a broader, flatter curve with higher positive values, suggesting generally larger and more variable first phalanges at this earlier settlement site. The Hofstaðir distribution occupies an intermediate position, with a moderately peaked curve centered closer to zero.

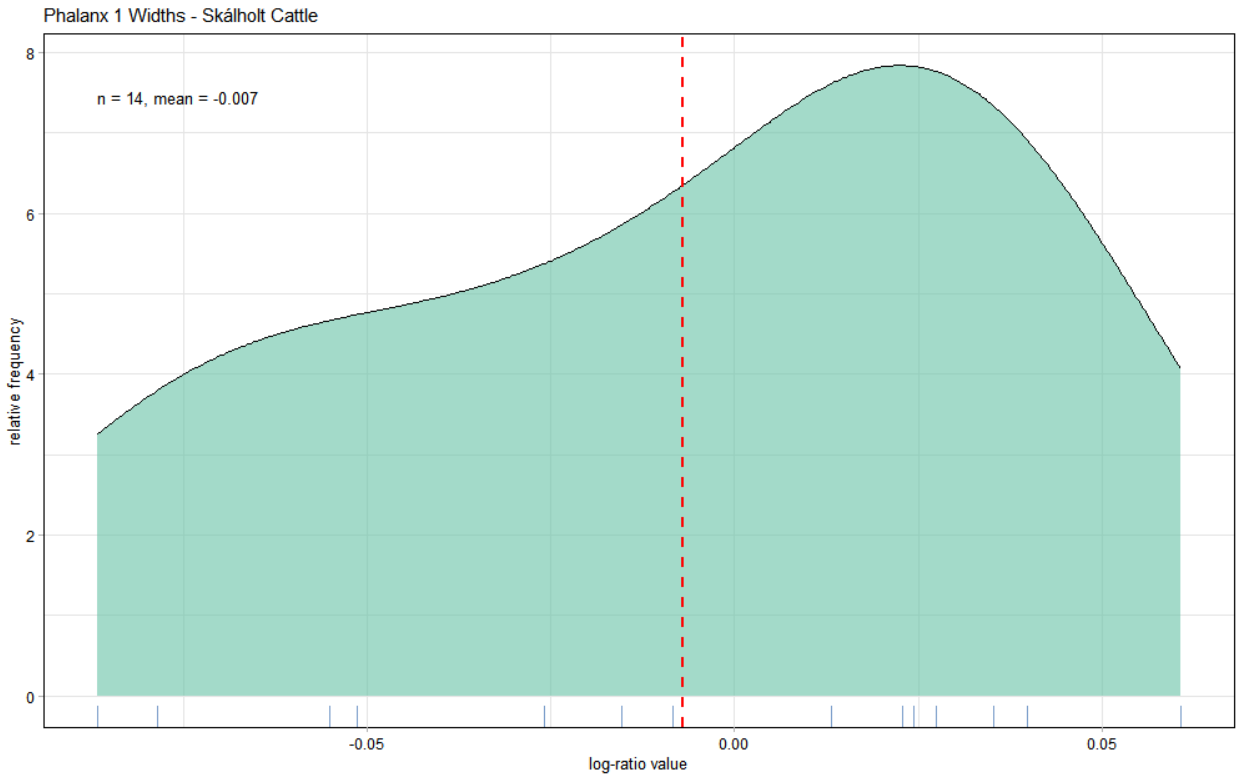

Figure 6.4. Log-ratio of phalanx 1 widths - Skálholt cattle.

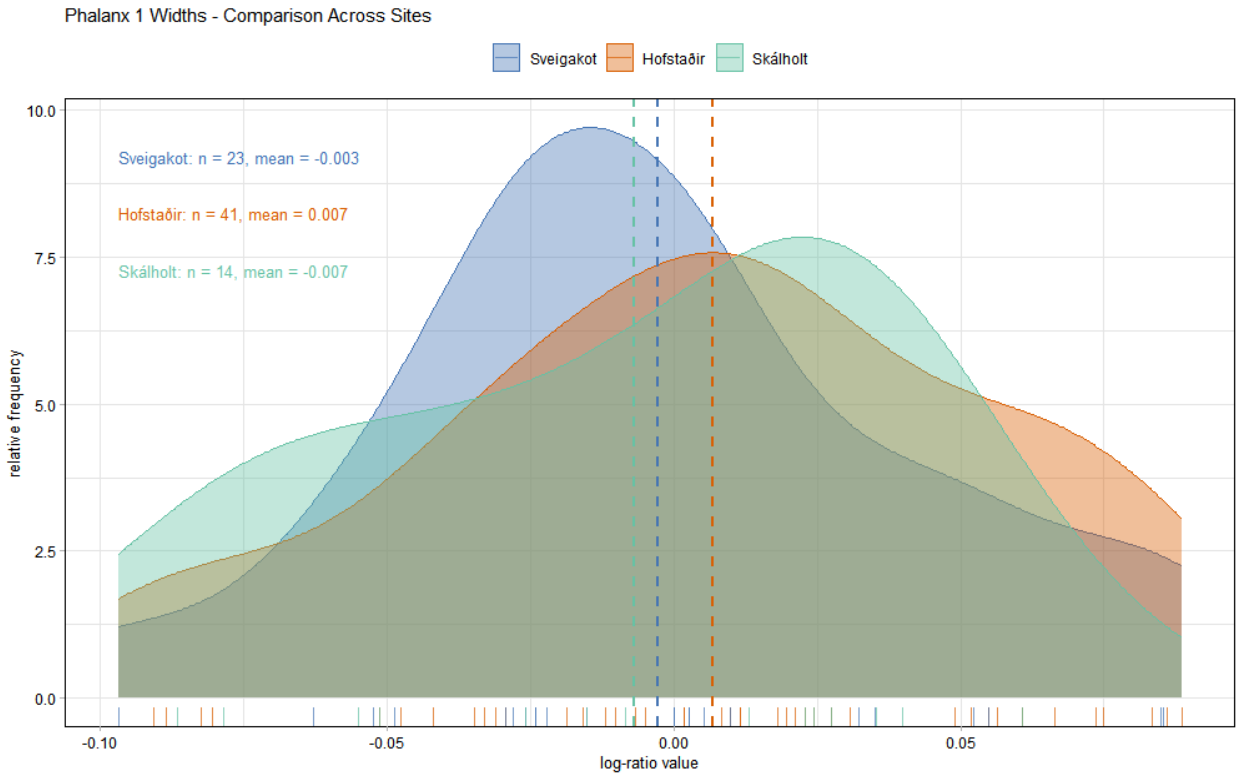

Figure 6.5. Log-ratio of phalanx 1 widths - comparison across Icelandic sites.

This chronological pattern – from larger, more variable first phalanges at earlier settlement sites to more standardized, slightly smaller dimensions at Skálholt – aligns with broader temporal trends observed in other skeletal elements. The greater standardization evident in the Skálholt assemblage potentially reflects more consistent management practices during the early modern period, while the reduced dimensions may indicate adaptation to environmental constraints that intensified following initial settlement. Alternatively, this pattern might reflect different demographic compositions between sites, with potentially greater representation of male cattle at the earlier settlements compared to Skálholt.

The contextual isolation and relatively modest sample size (n = 14 total across all contexts) limits our ability to draw robust conclusions regarding these elements in broader comparative frameworks. Consequently, while these measurements provide valuable supplementary data regarding cattle morphology, particularly regarding chronological changes in phalanx dimensions, they are excluded from more comprehensive comparative analyses with other Icelandic and North Atlantic assemblages, where phalanges are similarly underrepresented in biometrical datasets.

6.1.2 Evidence for Beef Production

Previous zooarchaeological analyses at Skálholt have illustrated a distinctive pattern of cattle management during the seventeenth and eighteenth centuries that includes unusually high percentages of cattle elements and evidence of selective breeding practices such as artificial polling (Hambrecht 2011, 2012). To further this line of inquiry, postcranial log-scaled measurements are interrogated with a series of

statistical tests to observe evidence for bulls or oxen or steers that might support previous hypotheses about specialized beef production that sharply distinguished Skálholt from the dairy-focused economy typical of contemporary Iceland.

Statistical analyses were conducted on width measurements across seven postcranial skeletal elements (astragalus, metacarpal, metatarsal, humerus, radius, femur, tibia). Sample sizes vary considerably among elements, with humeri and tibiae having the largest samples (n = 18 each) and astragali having the smallest (n = 3). Initial Shapiro-Wilk tests for normality revealed that while most elements showed normal distributions (femur: p = 0.879; radius: p = 0.722; humerus: p = 0.200; metatarsal: p = 0.052; metacarpal: p = 0.463), both tibia (p = 0.030) and astragalus (p = 0.028) departed significantly from normality. Given these mixed results, non-parametric tests were employed for subsequent analyses (Figure 6.6).

Given the strength of the relationship between metacarpals, femora, and humeri, a Kruskal-Wallis test indicated significant differences in width measurements among the elements (χ^2 = 18.775, df = 6, p = 0.005; Table 6.3). Metacarpal width measurements differed significantly from both femur and humerus measurements, with metacarpals showing consistently higher values. The metacarpal sample (n = 4) exhibited the highest mean width (0.0712 ± 0.0224) with relatively low variability, showing a narrow interquartile range (Q1 = 0.0542 to Q3 = 0.0839) and all measurements falling within a positive range (0.0515 to 0.0994). In contrast, femur measurements (n = 12) displayed negative mean values (-0.0172 ± 0.0290) with an interquartile range from -0.0324 to -0.00139. The difference between metacarpal and femur was highly significant (p = 0.0131). Humerus measurements (n = 18) showed

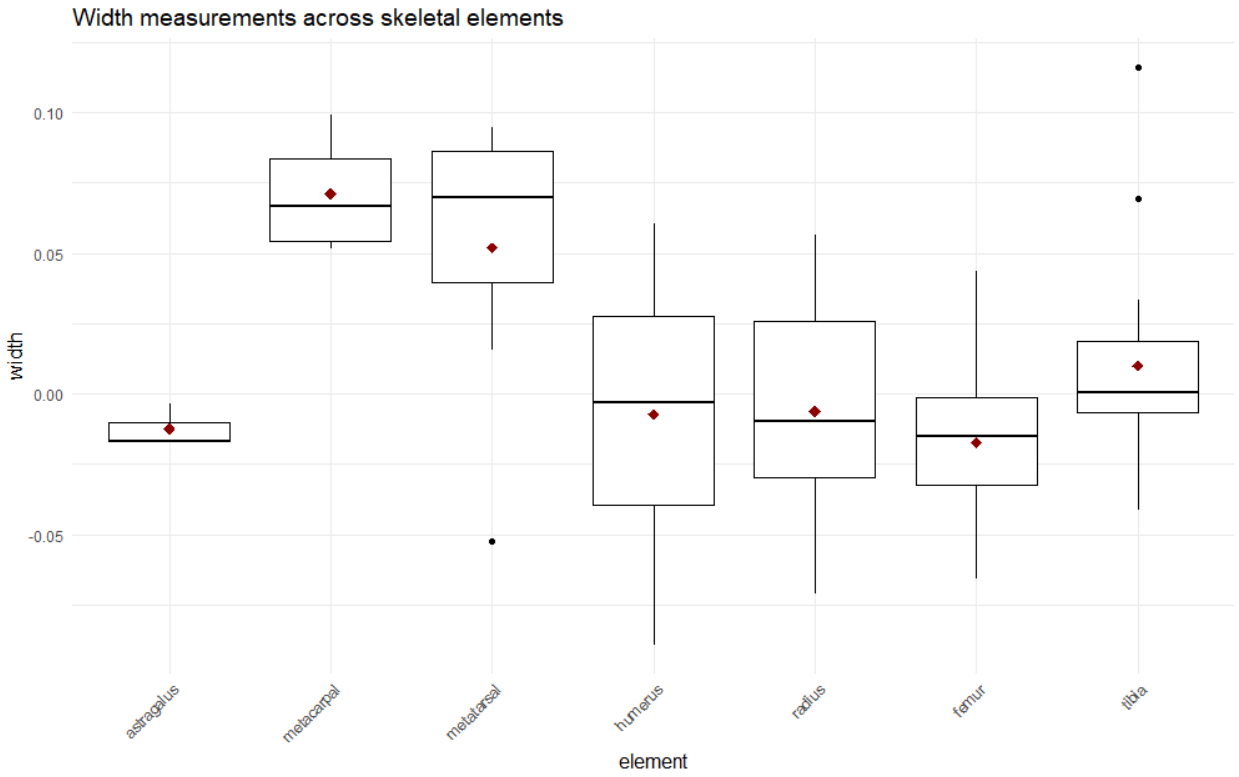

Figure 6.6. Log-ratio width measurements of Skálholt cattle - Midden Zone C.

an intermediate pattern with a mean closer to zero (-0.00724 ± 0.0466) but exhibited the highest variability of the three elements, with the widest interquartile range (-0.0394 to 0.0276) and the most extreme minimum value (-0.0892). The difference between metacarpal and humerus measurements was also significant ($p = 0.0419$), though less pronounced than the metacarpal-femur comparison (Figure 6.7). While these results are statistically significant, the small sample size for metacarpal should be noted (Figure 6.8).

Table 6.3. Summary statistics - log-ratio width measurements for Skálholt cattle in Midden Zone C.

element	*n*	mean	SD	median	Q1	Q3	min	max
metacarpal (MC)	4	0.0712	0.0224	0.0669	0.0542	0.0839	0.0515	0.0994
humerus (HUM)	12	-0.0172	0.0290	-0.0151	-0.0324	-0.0014	-0.0660	0.0438
femur (FEM)	18	-0.0072	0.0466	-0.0031	-0.0394	0.0276	-0.0892	0.0604

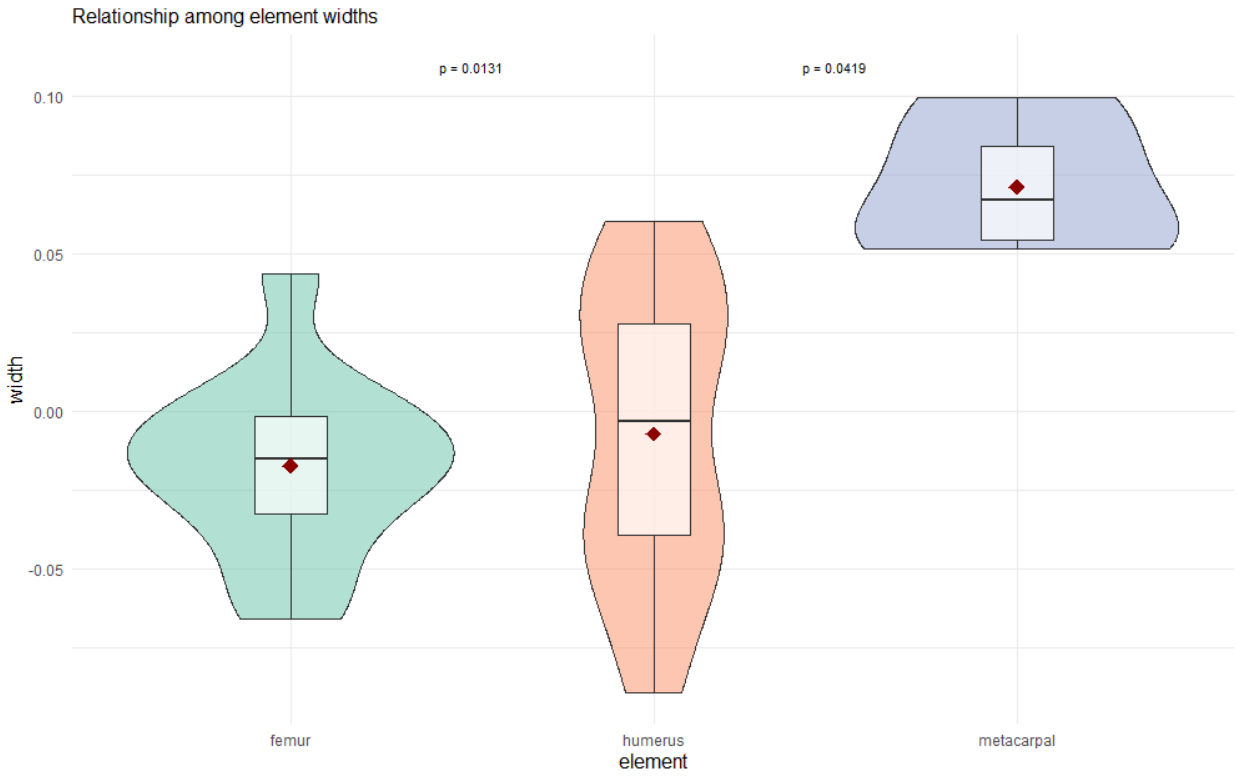

*Figure 6.7. Relationship among log-ratio width measurements of Skálholt cattle from Midden Zone C, comparing femur (*n = *12), humerus (*n = *18), and metacarpal (*n = *4) elements. The violin plots (colored outlines) visualize the probability density of the data at different values, showing distribution shape, while boxplots indicate median (horizontal line), interquartile range (box), and data range (vertical lines). Red diamonds represent mean values. Metacarpals show significantly higher width measurements compared to femur (p = 0.0131) and humerus (p = 0.0419), with less variability and consistently positive values, suggesting potential presence of male cattle (bulls or oxen) in the assemblage.*

The consistently wider metacarpal measurements at Skálholt may indicate the presence of male cattle, either bulls or castrates (oxen), as these animals typically exhibit greater bone width due to sexual dimorphism (Cussans 2010; Grau-Sologestoa

et al. 2021; Popovici et al. 2011; Thomas et al. 2013). This pattern is particularly noteworthy given the relatively low variability in the metacarpal measurements, suggesting a potentially deliberate selection or management strategy rather than random variation. The positive values for all metacarpal measurements, contrasting with the generally negative or near-zero values for femora and humeri, could indicate a specific subset of the cattle population with distinctly robust lower limb elements.

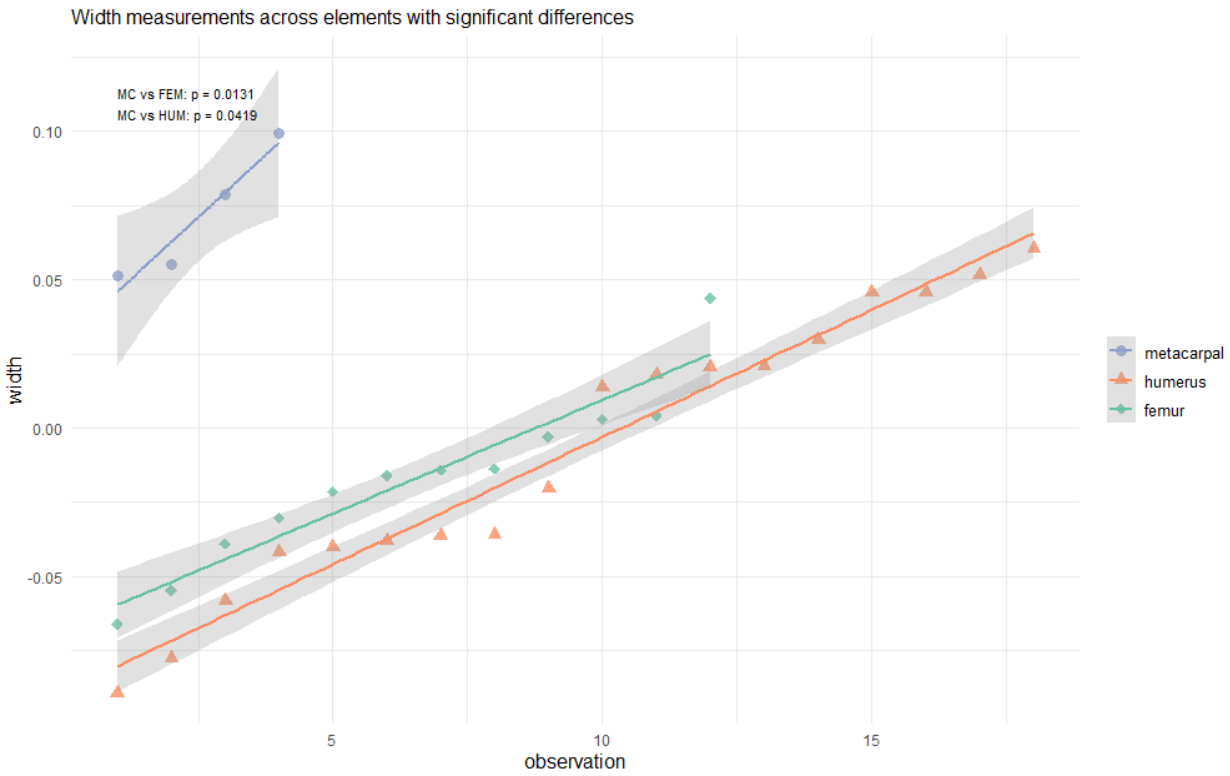

*Figure 6.8. Scatterplot showing relationship among log-ratio width measurements of Skálholt cattle from Midden Zone C for metacarpal (*n *= 4), humerus (*n *= 18), and femur (*n *= 12) elements. Each point represents an individual measurement, with colors distinguishing between element types. Metacarpals consistently show higher positive values (range: 0.0515 to 0.0994) with relatively low variability compared to the more widely distributed femur (range: -0.0660 to 0.0438) and humerus (range: -0.0892 to 0.0604) measurements.*

The presence of these wider metacarpals aligns with Skálholt's status as a high-status farm with substantial resources. The ability to maintain bulls or steers,

which provided a lesser return than cows (lacking abilities for birthing and dairying), would have been well within the capabilities of this wealthy center. If these measurements do represent oxen, they may reflect Skálholt's agricultural practices, particularly the use of draught animals for field cultivation. This interpretation is supported by historical evidence of oxen being valuable, if relatively rare, commodities for traction in medieval Iceland (Júlíusson 1997). Alternatively, if the measurements represent bulls, this could indicate specialized breeding practices or deliberate beef production, which would align with evidence suggesting Skálholt's emphasis on meat production over dairy.

6.1.3 Skálholt in the Icelandic Context

In many ways, the unique character of Skálholt's faunal assemblage makes it difficult to place it in conversation with a comparative site. The analysis of cattle bone measurements from *Landnám*-period and medieval Icelandic sites does, however, offer a window into understanding changes in livestock management across both space and time on the island during centuries of economic and ecologic change. This approach allows us to better understand not just the physical characteristics of Icelandic cattle, but also how their management reflected broader social, economic, and religious transitions in medieval Iceland. Based on this statistical analysis of cattle bone widths across the sites of Sveigakot, Hrísheimar, Hofstaðir, Gásir, and Skálholt, several interesting patterns emerge (Figures 6.9 and 6.10; Table 6.4).

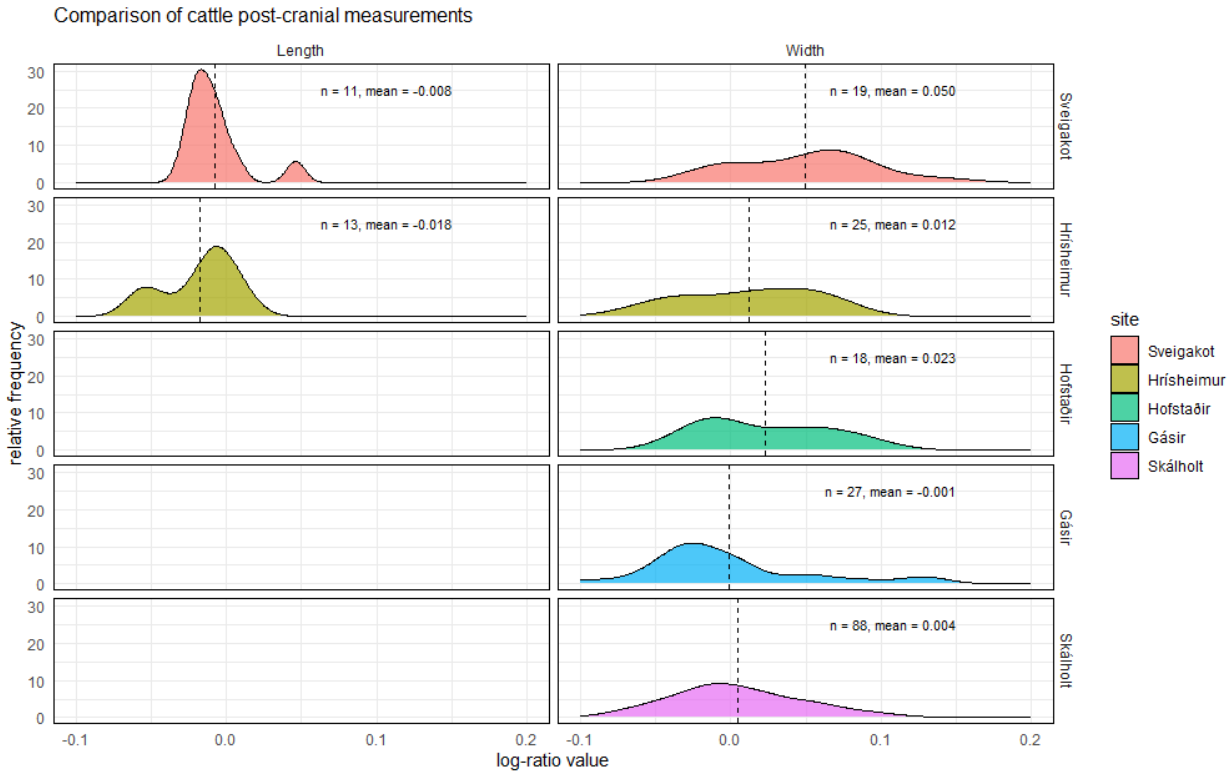

Figure 6.9. Log-ratio measurements of cattle at five Icelandic sites.

Table 6.4. Summary statistics - log-ratio measurements of cattle at five Icelandic sites.

site	*n*	mean	median	SD	min	max	CV
Sveigakot	19	0.0496	0.0513	0.0442	-0.0194	0.1442	89.11
Hrísheimar	25	0.0120	0.0148	0.0436	-0.0678	0.0780	363.33
Hofstaðir	18	0.0142	0.0142	0.0417	-0.0369	0.0975	293.66
Gásir	27	-0.0014	-0.0167	0.0545	-0.0963	0.1331	3892.86
Skálholt	88	0.0044	-0.0010	0.0436	-0.0892	0.1442	990.91

The analysis reveals that Sveigakot, despite being a lower-status site, had notably wider cattle bones compared to other sites, with the highest mean relative width (0.04957) and a consistent pattern shown by its similar median value (0.05130). The robust metacarpals at Sveigakot could indicate either better-nourished animals, the presence of more robust cattle in the earlier period of colonization, or a greater

representation of male cattle in the sample. This stands in particular contrast to Gásir, which showed the lowest mean relative width (-0.00137). The statistical significance of these differences was confirmed through both Kruskal-Wallis testing ($p = 0.001449$) and subsequent Dunn's post-hoc analysis, which specifically highlighted the significant differences between Sveigakot and both Gásir and Skálholt (Table 6.5).

Table 6.5. Normality tests (Shapiro-Wilk) for cattle widths.

site	*W*	p value	normal distribution?
Sveigakot	0.90355	0.01615	no
Hrísheimar	0.92675	0.17020	yes
Hofstaðir	0.95083	0.26180	yes
Gásir	0.98810	0.60760	yes
Skálholt	0.95259	0.43690	yes

The distribution patterns across sites reveal interesting social and economic distinctions. Four of the five sites (Sveigakot, Hrísheimar, Hofstaðir, and Skálholt) exhibit normal distributions in their measurements, while Gásir does not (Harrison 2008, 2009). This deviation from normality at Gásir ($p = 0.01615$) likely reflects its role as a seasonal trading center, where cattle would have been brought in from surrounding farms or as provisions. The mixed origins of these animals would naturally result in more varied bone measurements, creating the observed non-normal distribution pattern.

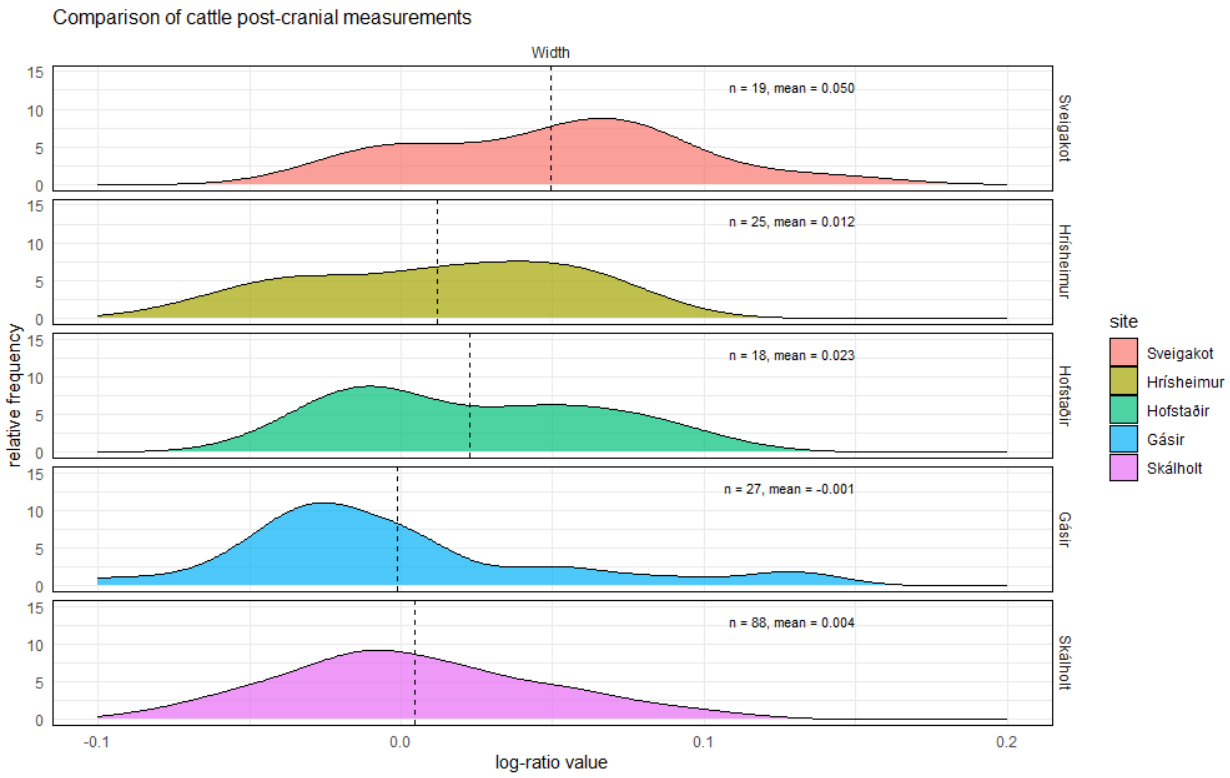

Figure 6.10. Log-ratio width measurements of cattle at five Icelandic sites

Hofstaðir presents an intriguing case as a high-status site, where the cattle bones were mostly from relatively large cattle, possibly connected to pre-Christian ritual activity (McGovern et al. 2009, 2013). While the robust size might suggest these were bulls, aDNA evidence indicates that at least one was a cow (Hambrecht, personal communication 2025). Meanwhile, at Hrísheimar, a *Landnám*-period site, the cattle bones tend to be smaller than nineteenth-century comparative specimens, suggesting changes in cattle size over time (McGovern et al. in press). Skálholt provides particularly robust data due to its large sample size (n = 88), significantly larger than other sites which ranged from 18-27 samples. Its mean values close to

zero (0.00435) might represent something close to a regional average, making it a useful baseline for comparing other sites.

The consistency in variance across all sites (ranging from 0.00174 to 0.00297) suggests reliable measurement practices across researchers recording over time and indicates that despite differences in absolute size, the range of variation within each site remained relatively stable. This could indicate consistent breeding practices within each location, even if the typical size of cattle differed between sites (Table 6.6).

Table 6.6. Variance analysis for cattle widths.

site	variance
Sveigakot	0.002974
Hrísheimar	0.001735
Hofstaðir	0.001896
Gásir	0.001899
Skálholt	0.001957

Despite its classification as a lower-status site, Sveigakot exhibits the highest mean relative width (0.04957) and median (0.05130) of all five sites analyzed, with these measurements being remarkably consistent as shown by the similarity between these mean and median values. This consistency is further supported by the normal distribution of its measurements and a variance (0.001957) that aligns closely with other sites. However, it is more appropriate to approach the variance in the Sveigakot data as a function of time and ecology rather than simply status. The site was occupied from the beginning of the *Landnám* period around 875 AD and continued through approximately 1000 AD, with occupation becoming sparse thereafter. The site's initial establishment coincided with the *Landnám* period, when settlers were

first adapting their livestock management strategies to Iceland's marginal environment (Cesario 2021; McGovern et al. 2007; Thomson and Simpson 2007). The site underwent significant changes during its occupation, transitioning from sunken-featured buildings to a small hall in the late tenth century and then experiencing abandonment before reoccupation in the late eleventh century.

Sveigakot's relationship with cattle changed over time. Cattle bone relative percentages decline from a high around 35 percent in the earliest deposits (c. 875-930 AD) to 20 percent in the eleventh century (McGovern et al. 2009). This substantial shift in herd composition, combined with evidence of diverse feeding strategies (as shown by isotope analysis of pig bones at the site – McGovern et al. in press), suggests a dynamic and adaptable approach to livestock management. The zooarchaeological evidence indicates changes over time, possibly associated with declining status or tenantry, with an emphasis on wool production in later phases (Thomson and Simpson 2007).

The larger metacarpal measurements could indicate better-nourished animals, suggesting that despite its lower status, Sveigakot may have had access to superior grazing lands or fodder resources (Cussans 2010). However, evidence from tooth wear patterns complicates this picture - the Sveigakot cattle show different third molar wear patterns compared to both Hofstaðir and Gásir, suggesting they may have grazed on rougher or more eroded pastures and experienced more rapid dental attrition as adults (McGovern et al. 2009). The robust bone width is contrasted with evidence of unfavorable grazing conditions, presenting a challenge to our understanding of cattle management at the site. Alternatively, the wider bones could

reflect a greater representation of male cattle in the sample. This possibility is particularly intriguing when we consider that the measurements are significantly different from both Gásir ($p = 0.0008$) and Skálholt ($p = 0.0015$) but show only marginal differences from Hrísheimar ($p = 0.0756$). This could suggest a distinct cattle management strategy at both Sveigakot and Hrísheimar, as early sites located in the same region, that perhaps focused on maintaining more males for traction or meat production rather than dairying (Figure 6.11).

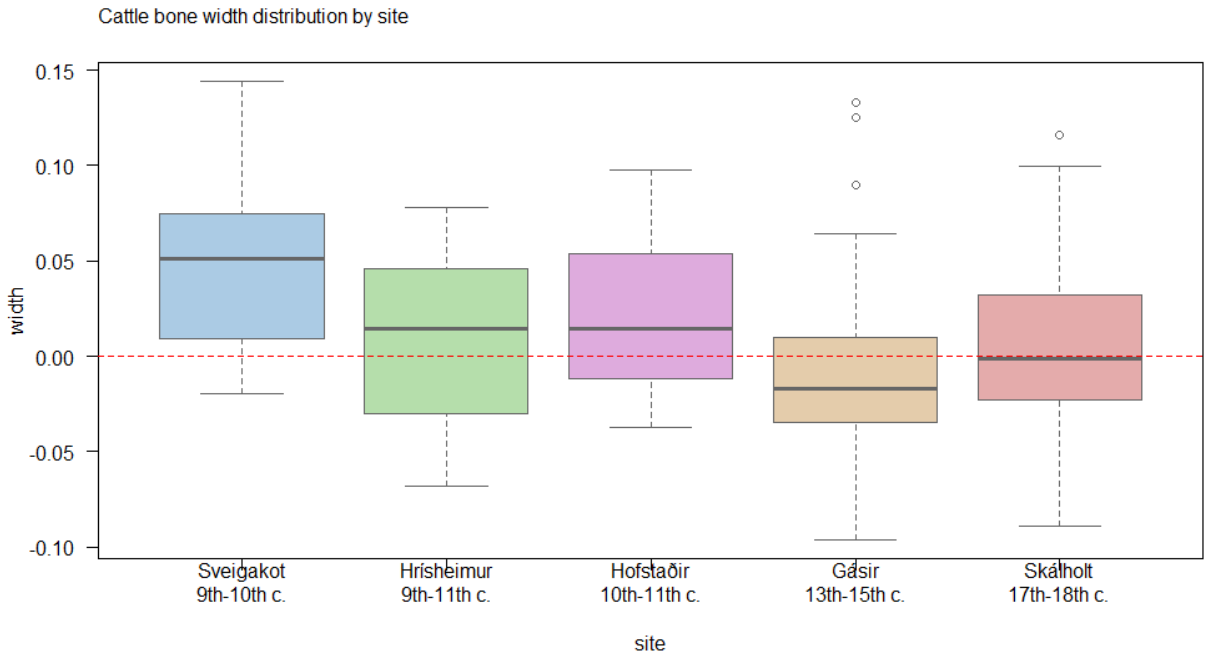

Figure 6.11. Boxplots of log-ratio width measurements for cattle at five Icelandic sites.

The normal distribution of measurements at Sveigakot, combined with its consistent variance (0.001957), suggests these patterns reflect deliberate management practices rather than random variation. Unlike Gásir, where the non-normal

distribution suggests mixed cattle origins, Sveigakot's pattern points to a stable, locally-managed herd. This consistency in measurement distribution, combined with the evidence for declining cattle percentages over time, might indicate a carefully managed breeding program that maintained consistent cattle characteristics even as the overall herd size decreased.

6.1.4 Skálholt in the North Atlantic Context

Having examined the patterns of cattle bone measurements across medieval Icelandic sites, we can now broaden our perspective by incorporating comparative data from other North Atlantic regions. This wider view, including data from Greenland settlements and Leicester city center in England, allows us to situate the Icelandic patterns within a broader context of medieval North Atlantic livestock management. The English data is particularly valuable as it comes from a period of agricultural improvement, while the Greenland data offers insights from a roughly contemporary but environmentally distinct Norse settlement area (Table 6.7).

Table 6.7. Summary statistics - log-ratio measurements of cattle at seven North Atlantic sites.

site	*n*	mean	median	SD	min	max	CV
Sveigakot	19	0.0496	0.0513	0.0442	-0.0194	0.1442	89.11
Hrísheimar	25	0.0120	0.0148	0.0436	-0.0678	0.0780	363.33
Hofstaðir	18	0.0142	0.0142	0.0417	-0.0369	0.0975	293.66
Greenland-W	64	0.0311	0.0280	0.0482	-0.0596	0.1640	155.31
Gásir	27	-0.0014	-0.0167	0.0545	-0.0963	0.1331	3892.86
The Shires	108	0.0439	0.0373	0.0497	-0.0933	0.1915	113.21
Skálholt	88	0.0044	-0.0010	0.0436	-0.0892	0.1442	990.91

Greenland's Western Settlement

The Norse settlements in western Greenland serve as a comparative sample to explore North Atlantic cattle management (Cussans 2010; McGovern 1985). The bone measurements come primarily from ordinary farm sites with associated middens and all Western Settlement assemblages included in this analysis are dated to the fourteenth and fifteenth centuries, up to the end of the occupation of these farms. V51 (Sandnes), a high-status church farm, offers additional data from the later settlement period (McGovern 1985). Together, these Western Settlement sites, characterized by their interconnecting building complexes and higher proportion of dogs and caprines compared to other Norse settlements, are representative of the adaptation of Norse farming practices to Greenland's environment (McGovern et al. 2014).

The Shires, Leicester

The Shires dataset derives from two sites in central Leicester's Highcross district excavated in 1988 and 1989 (Lucas and Buckley 2007; Grau-Sologestoa and Albarella 2019). With 108 cattle measurements, this substantial urban sample spans the late medieval to early post-medieval periods (fourteenth to seventeenth centuries). The material, preserved in the Leicester Museum, represents one of the larger comparative assemblages in this analysis and provides valuable insights into urban cattle management practices in medieval England (Gidney 1991a, b, c, 1992, 1993). These sites offer an important contrast to our North Atlantic farm sites, representing cattle management in a developed urban center rather than in frontier or rural settings.

The descriptive statistics highlight distinct characteristics among the sites. Sveigakot exhibited the highest mean width (0.0496), while Gásir was the only site with a slightly negative mean (-0.0014). The coefficient of variation (CV) showed remarkable variability, with most sites displaying relatively low CV values, except for Greenland and The Shires, which showed more substantial relative variation (Figure 6.12, Table 6.8). This pattern of variation could reflect different management strategies or population compositions at these sites.

Table 6.8. Summary of statistical test results for North Atlantic cattle width measurements.

test	statistic	p-value	interpretation
Shapiro-Wilk Normality	varied	0.0161-0.639	most sites normally distributed; Gásir significantly deviates
Levene's Variance Test	F = 0.1943	0.9783	homogeneous variances across sites
One-way ANOVA	F = 8.449	1.46e-08	highly significant differences between sites
Kruskal-Wallis Test	χ^2 = 46.246	2.65e-08	confirms significant site differences

Normality testing revealed that most sites approximated a normal distribution, with Gásir emerging as a statistical outlier. The Shapiro-Wilk test indicated significant deviation from normality for Gásir ($p = 0.0161$), suggesting unique morphological characteristics or potential sampling peculiarities at this site. This non-normal distribution at Gásir could reflect its role as a trading center, where cattle from various sources might have been present. Despite individual site variations, Levene's test for homogeneity of variances demonstrated no significant differences in measurement spread ($p = 0.9783$). This consistency in variability provided a robust

foundation for subsequent comparative analyses and suggests some standardization in cattle populations across sites, even if the absolute sizes differed.

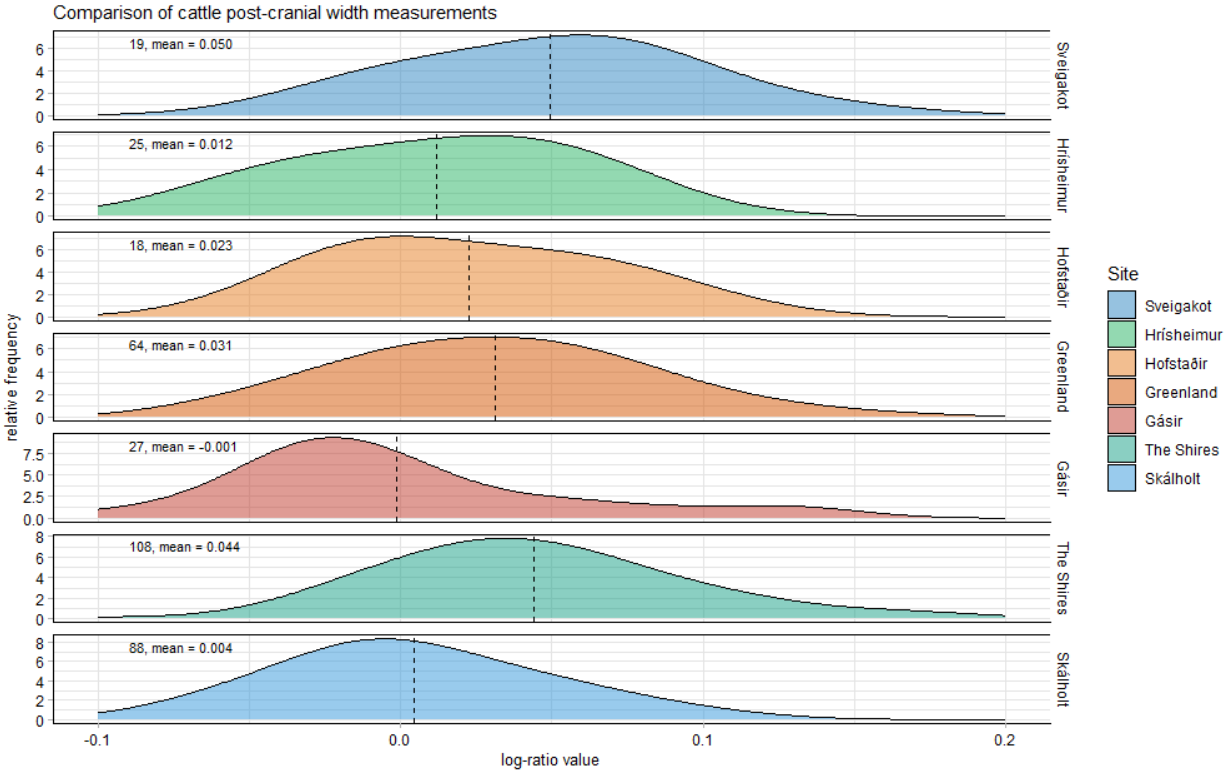

Figure 6.12. Log-ratio measurements of cattle at seven North Atlantic sites.

Both parametric (ANOVA) and non-parametric (Kruskal-Wallis) tests consistently revealed highly significant differences among sites ($p < 0.001$). The one-way ANOVA yielded an F-statistic of 8.449, while the Kruskal-Wallis test produced a chi-squared value of 46.246, both indicating substantial inter-site variation in cattle width measurements. Post-hoc pairwise comparisons highlighted specific significant differences, with Gásir demonstrating statistically significant differences when

compared to Greenland, Hofstaðir, and The Shires, while Sveigakot showed significant variations when compared to Gásir, Hrísheimar, and Skálholt.

These statistical patterns reveal that cattle dimensions in medieval and early modern Iceland reflected complex interactions between settlement chronology, site function, and management priorities rather than simply indicating status differences. The unexpected robusticity of cattle remains at Sveigakot despite its lower status, and the smaller dimensions at the trading center of Gásir, challenge straightforward correlations between site status and animal size. Instead, temporal factors (with earlier sites showing larger cattle) and functional differences (trading centers versus farms) appear more influential in shaping cattle morphology.

The consistent variance across all sites despite differences in absolute dimensions suggests stable breeding practices within each location throughout their occupation periods. This homogeneity within populations, coupled with the systematic differences between sites, indicates deliberate management strategies tailored to specific environmental and economic conditions rather than random variation. Skálholt's intermediate position and normal distribution pattern likely reflects its role as an ecclesiastical center that received livestock from other sites, maintaining standardized husbandry practices while adapting to Iceland's environmental conditions.

6.1.5 England's "Long" Sixteenth Century

The log-scaled width measurements from both Skálholt and The Shires exhibit normal distributions, as confirmed by Shapiro-Wilk tests (Figure 6.13). For Skálholt:

$W = 0.988$, p = 0.608. And The Shires results were equally strong: $W = 0.981$, p = 0.123. The high p-values (> 0.05) and W-values close to one indicate a strong degree of normality in both populations. Additionally, the homogeneity of variance was assessed using Levene's test, resulting in an F-value of 0.767 and p = 0.382, further attesting to the equal variances between the cattle widths at the two sites.

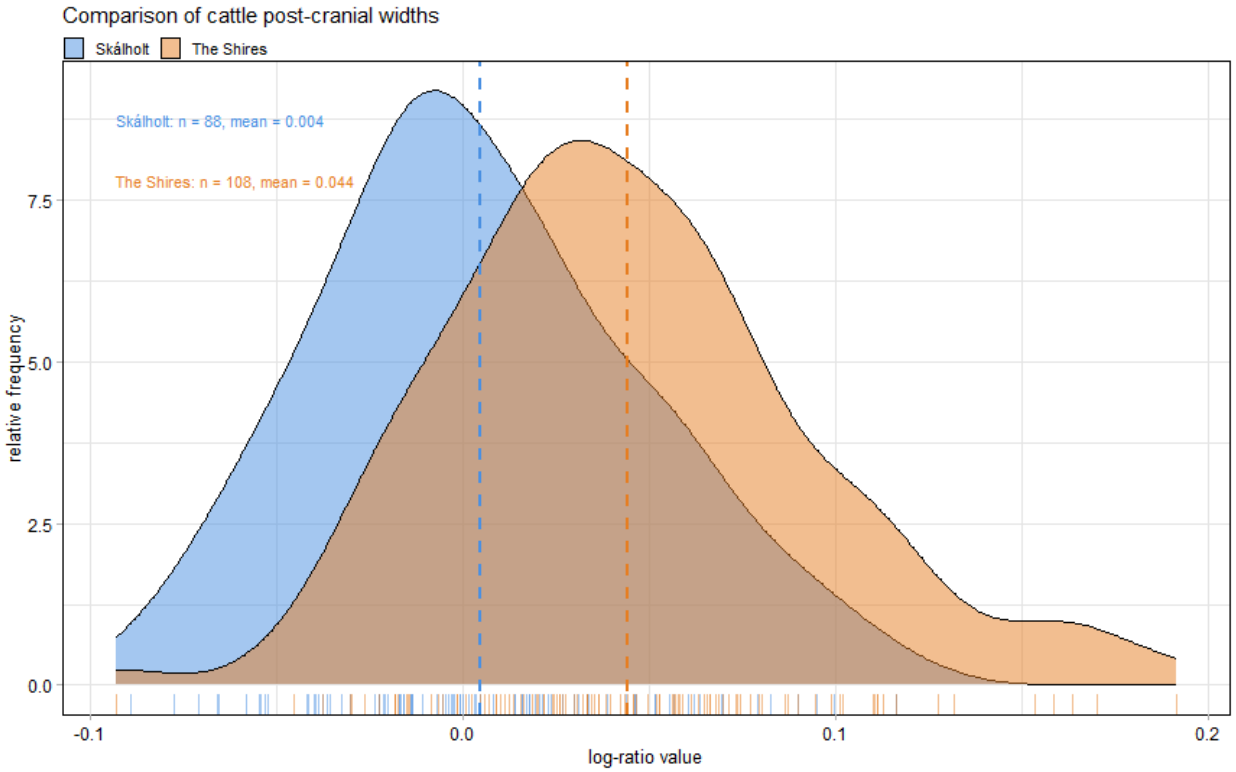

Figure 6.13. Comparison of cattle post-cranial width measurements from Skálholt and The Shires.

Despite the shared reference standard and normal distributions, statistical analyses revealed significant differences in cattle post-cranial widths between Skálholt and The Shires. A one-way ANOVA yielded an F-value of 34.29 and a p-value of 2e-08 ($p < 0.001$), indicating a highly significant difference. The effect size, measured by Cohen's δ, was -0.841 (95% CI: [-1.136, -0.546]), suggesting a large

and practically meaningful difference, with The Shires cattle exhibiting larger width measurements compared to Skálholt.

The mean log ratio for Skálholt cattle was close to zero, with the peak of the distribution slightly below zero, indicating that the width measurements were similar to the Bronze Age reference standard, with some variability below that baseline (Nieto-Espinet 2018). In contrast, The Shires cattle showed log ratio values above zero, suggesting an increase in bone width compared to the reference specimen.

The "long" sixteenth century in England witnessed significant advancements in animal husbandry and is often considered the beginning of the Second Agricultural Revolution (Davis 1997; Davis and Beckett 1999; Grau-Sologestoa and Albarella 2019; Kerridge 1967; Overton 1996; Thomas 2005). This period was characterized by a gradual but notable increase in livestock size, particularly in cattle, driven by factors such as selective breeding, introduction of new breeds, and improved feeding practices (Albarella 1997; Thomas 2005; Thomas et al. 2013).

The statistical analyses of the log-scaled width measurements reveal a significant difference between the cattle populations of Skálholt and The Shires. The markedly larger size of The Shires cattle, as evidenced by the high Cohen's δ value and the positioning of the log ratio values above zero (relative to the Bronze Age reference cow), strongly suggests that the cattle in this region had undergone substantial improvement efforts. This aligns with the historical narrative of the Second Agricultural Revolution in England, where advancements in breeding practices and better nutrition led to increased livestock size (Kerridge 1967). In contrast, the Skálholt cattle, with a mean log ratio close to zero and a peak slightly

below zero, appear to have maintained a size more similar to the reference animal, indicating a lesser degree of size increase compared to The Shires.

However, the absence of a dramatic size increase in the Skálholt cattle does not necessarily imply a lack of engagement with the broader trends of agricultural improvement (Hambrecht 2011). The presence of both naturally and artificially polled cattle at the site, an unusual trait for the period, suggests that the bishops and others at Skálholt were actively involved in specialized husbandry practices and potentially "proto-Lamarckian" breeding strategies (Hambrecht 2012; Kjærgaard 1994). These practices, along with attempts at barley cultivation in the challenging Icelandic environment (Dugmore et al. 2007; McGovern et al. 2007), indicate a shift towards innovative practices aligned with the broader context of changing technologies and attitudes in early modern Europe (Hambrecht 2011).

While the Second Agricultural Revolution, exemplified by the substantial size increase in The Shires cattle, represents a more well-known narrative of agricultural transformation, the situation at Skálholt offers a valuable counterpoint. The evidence from Skálholt demonstrates that engagement with improvement concepts and practices was not limited to England and that local elites played a crucial role in adapting these ideas to their specific contexts. The more modest size increase observed in the Skálholt cattle, compared to The Shires, underscores the importance of considering regional variations, environmental constraints, and socio-cultural factors when assessing the impact and extent of livestock improvement efforts.

6.1.6 Withers Heights – Stature Reconstruction

The withers height estimates for cattle across our sites indicate some potential size differences between locations and time periods (von den Driesch and Boessneck 1974). Substantial variation exists in estimated withers heights across the studied sites (Table 6.9). The metacarpal-derived estimates range from 94.89 cm (minimum at Hrísheimar) to 122.39 cm (maximum at The Shires), while metatarsal-derived estimates span from 95.10 cm (minimum in Western Settlement) to 112.27 cm (maximum in Western Settlement). These ranges indicate considerable dimensional variability that exceeds what would be expected from sexual dimorphism alone, suggesting additional factors such as breeding practices, nutritional status, or environmental adaptations may have influenced cattle stature.

Table 6.9. Stature reconstruction for cattle.

site	element	*n*	min	max	mean	SD
Sveigakot	MC	9	101.41	120.36	106.96	5.6316
	MT	2	107.86	109.98	108.92	1.5030
Hrísheimar	MC	8	94.89	111.62	103.49	6.9417
	MT	2	109.71	109.87	109.79	0.1156
Hofstaðir	MC	2	104.24	110.82	107.53	4.6531
	MT	1	107.15	107.15	107.15	
Western Settlement	MC	28	92.25	118.08	104.26	5.8776
	MT	16	95.10	112.27	104.98	3.9192
Gásir	MC	1	107.93	107.93	107.93	
	MT	2	110.09	110.36	110.64	0.3854
The Shires	MC	4	109.47	122.39	115.79	5.3250
Skálholt	MT	3	104.01	108.46	105.70	2.4040

The site-specific patterns are particularly informative. The Shires (England) demonstrates the tallest mean withers height based on metacarpal measurements

(115.79 cm), substantially exceeding the means calculated for Icelandic sites: Sveigakot (106.96 cm), Hofstaðir (107.53 cm), and Gásir (107.93 cm) (Figure 6.14). This substantial height difference – approximately 8-9 cm – between English and Icelandic specimens aligns with documentary evidence for agricultural improvement in England during the "long" sixteenth century, suggesting potential breed improvements had substantively altered cattle dimensions in this region compared to the more isolated Icelandic populations (Grau-Sologestoa and Albarella 2019).

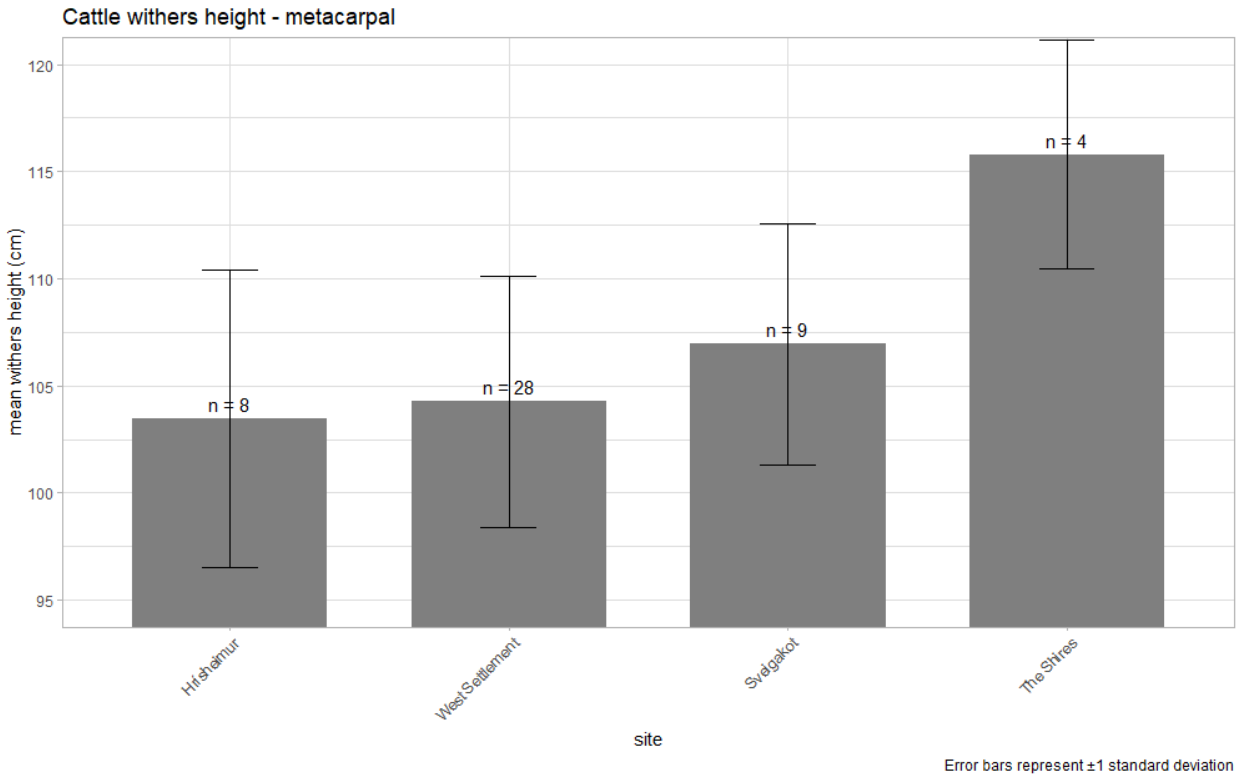

Figure 6.14. Cattle withers height - metacarpal.

Within Iceland, the cattle from earlier sites (Sveigakot, Hrísheimar, and Hofstaðir) show relatively similar mean withers heights despite their different status

levels. This pattern suggests that during the settlement and medieval periods, cattle maintained relatively consistent dimensions across different site types. Interestingly, Skálholt cattle (measured only through metatarsals, with only $n = 3$) show a mean value (105.70 cm) slightly below that of earlier Icelandic sites (Figure 6.15). This stands in contrast to the evidence from sheep, where Skálholt specimens demonstrated increased dimensions compared to earlier sites. This differential pattern between sheep and cattle may reflect divergent management priorities during the early modern period, with potential intensification of sheep improvement while maintaining more traditional cattle husbandry practices.

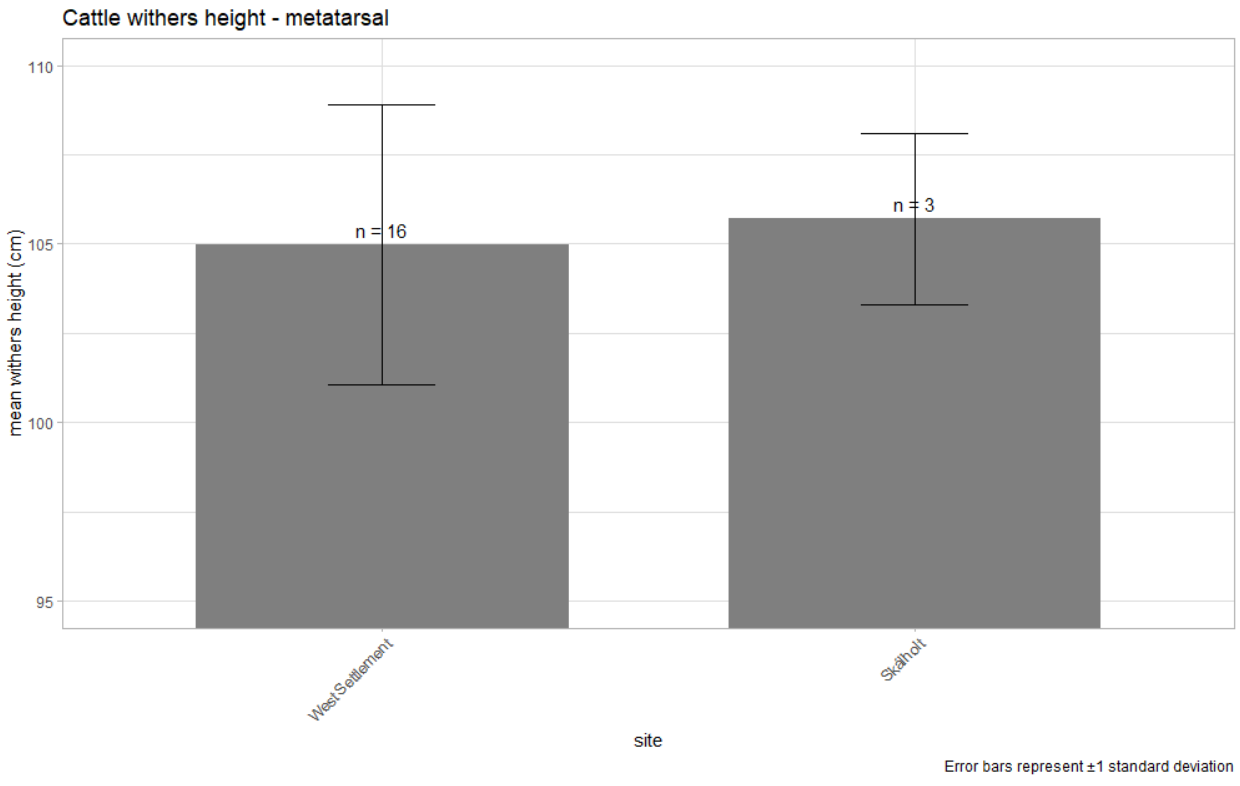

Figure 6.15. Cattle withers height - metatarsal.

The Western Settlement material presents an interesting case, with substantial sample sizes for both metacarpals (n = 28) and metatarsals (n = 16) allowing more robust analysis. The mean withers heights (metacarpals = 104.26 cm; metatarsals = 104.98 cm) fall below those of most Icelandic sites, potentially reflecting the more marginal conditions in Greenland. However, the ranges are considerable (metacarpals: 92.25-118.08 cm; metatarsals: 95.10-112.27 cm), suggesting substantial variation within the population. This wide distribution might indicate mixed breeding stock, differential access to nutrition between higher and lower status farms, or preservation of both early and late specimens showing temporal change in dimensions.

Statistical comparison between the Western Settlement and Skálholt metatarsal measurements yields a p-value of 0.687 ($t = -0.4235$, $df \approx 6$), indicating no statistically significant difference between these populations despite the apparent dimensional disparity (104.98 cm vs. 105.70 cm). However, this result must be interpreted with extreme caution due to the very small sample size from Skálholt (n = 3) compared to the Western Settlement (n = 16). The limited Skálholt sample substantially reduces statistical power, creates unreliable standard deviation estimates, and produces wide confidence intervals. These statistical limitations prevent definitive conclusions regarding dimensional differences between these assemblages, despite the observed mean differences. This uncertainty exemplifies a common challenge in zooarchaeological analyses, where sample size constraints frequently limit the statistical robustness of comparative studies, particularly for complete elements suitable for withers height reconstruction.

The standard deviations provide additional insights into population characteristics. For metacarpal-derived estimates, The Shires shows relatively high variability (SD = 5.3250) despite the small sample size (n = 4), suggesting potential diversity in cattle types during this period of agricultural transformation. The Western Settlement demonstrates similarly high variation (SD = 5.8776 for metacarpals), potentially reflecting the mixed origins of imported stock or differential management practices across the settlement. By contrast, Skálholt shows more modest variation in metatarsal-derived estimates (SD = 2.4040), suggesting a more homogeneous population, which aligns with evidence for polledness and potential selective breeding at this site (Hambrecht 2011, 2012).

When examining the withers height distributions visually, several patterns become apparent (Figures 6.14 and 6.15). The English specimens from The Shires consistently cluster at the upper end of the height range, reinforcing their distinctive status compared to North Atlantic specimens. The Western Settlement specimens show the widest distribution, spanning nearly the entire range of observed heights. The Icelandic specimens generally cluster in the middle of the range, with substantial overlap between different sites suggesting general continuity in cattle dimensions throughout the medieval period.

These withers height patterns correlate with the log-ratio analysis presented earlier, where The Shires demonstrated the highest mean (0.0439) for cattle width measurements, substantially exceeding those from Skálholt (0.00435) and other Icelandic sites. The combination of taller withers heights and larger width measurements at The Shires provides strong evidence for breed improvement in

England during this period, contrasting with the more modest dimensional changes observed in Icelandic cattle.

The smaller stature of Skálholt cattle compared to both contemporary English specimens and earlier Icelandic examples is particularly noteworthy given the site's elite status and evidence for agricultural innovation. This pattern suggests limited improvement or introduction of new cattle breeds during this period, despite the site's ecclesiastical significance and access to broader European networks. The evidence instead indicates adaptation to Icelandic conditions rather than importation of larger European breeds, with management efforts potentially focused more on specialized breed characteristics like polledness rather than simple size maximization (Hambrecht 2012).

These findings highlight the complex interaction between human management decisions, environmental constraints, and economic priorities in shaping livestock morphology across different North Atlantic settings. While English cattle showed substantial size increases during this period, reflecting the agricultural changes of the "long" sixteenth century, Icelandic populations appear to have maintained more traditional dimensions with selective emphasis on specific characteristics like polledness rather than overall size enlargement, though sample size limitations necessitate caution in drawing definitive comparative conclusions.

6.1.7 Cattle Summary

The biometrical analysis of Skálholt's cattle assemblage reveals several distinctive patterns with implications for understanding early modern livestock

management practices in Iceland. The statistical examination of postcranial widths demonstrates that Skálholt's cattle generally aligned with contemporary Icelandic populations in overall dimensions while exhibiting specific morphological characteristics that suggest specialized management strategies. The consistently wider metacarpal measurements relative to other skeletal elements, particularly when compared to femora and humeri, indicates a potential emphasis on robust lower limb elements that may reflect deliberate selection for particular functional traits or breeding priorities.

When situated within the broader Icelandic context, Skálholt's cattle occupy an intermediate position between the notably larger specimens from early settlement sites like Sveigakot and the smaller animals documented at specialized trading centers like Gásir. This dimensional pattern challenges straightforward correlations between site status and animal size, suggesting that functional differences and temporal factors exerted more significant influence on cattle morphology than simple status hierarchies. The relatively stable variance observed across all Icelandic sites, despite differences in absolute dimensions, indicates consistent breeding practices within each location throughout their respective occupation periods.

The comparison with contemporaneous English material from The Shires provides valuable insights into Skálholt's relationship with broader European agricultural developments. The substantial dimensional difference between these assemblages demonstrates that while England experienced significant livestock size increases during the "long" sixteenth century, Icelandic cattle, even at elite centers like Skálholt, followed a more conservative morphological trajectory. However, this

apparent conservatism in overall dimensions should not be interpreted as evidence for isolation from European agricultural innovation. Rather, the presence of both naturally and artificially polled specimens at Skálholt, combined with evidence for potential selective breeding practices, suggests engagement with improvement concepts, albeit adapted to Iceland's specific environmental constraints and economic priorities.

This pattern aligns with documentary evidence regarding agricultural improvement efforts at Skálholt during the seventeenth and eighteenth centuries. Together, the zooarchaeological and historical evidence suggests that Skálholt represented a locus of agricultural innovation within Iceland, where European improvement concepts were selectively adapted rather than wholesale adopted. The biometrical evidence thus reveals not simple emulation of English improvement models, but rather a distinctively Icelandic engagement with broader agricultural change – one that prioritized specific adaptations like polledness over the dramatic size increases documented in contemporary English contexts.

6.2 Sheep

Unlike cattle, which represented a proportionally smaller yet significant component of the Skálholt economy, sheep constituted the foundation of Iceland's pastoral economy throughout the medieval and post-medieval periods (McGovern et al. 2007). Their capacity to utilize marginal grazing lands, combined with their value for both wool, dairy and meat production, made sheep particularly central to ecclesiastical estates with extensive landholdings (Hambrecht 2011; Lucas and Snæsdóttir 2022). This section examines the morphological characteristics of Skálholt's sheep assemblage through log-ratio scaling techniques, comparing dimensional patterns with both internal contexts at Skálholt and broader regional frameworks extending across Iceland and the North Atlantic. This analysis addresses several fundamental questions regarding livestock improvement, specialized production strategies, and potential engagement with European agricultural innovations during a period of significant economic transition in early modern Iceland.

6.2.1 The Skálholt Sheep

The sheep metrics assemblage from Skálholt shows distinct patterns in both length and width measurements across various post-cranial elements. Length measurements ($n = 63$, mean = 0.033) and width measurements ($n = 188$, mean = 0.019) both demonstrate positive log-ratio values, suggesting these animals were generally larger than the Soay standard reference specimen (Figure 6.16). The significant difference in sample sizes between length and width measurements ($p = 0.00502$)

reflects common preservation and measurement challenges in zooarchaeological assemblages.

A Welch Two Sample t-test confirms a significant difference between length and width measurements ($t = 2.848$, $df = 149.29$, p-value = 0.00502). This highly significant p-value indicates a strong statistical distinction between these measurement categories. The mean for length measurements (0.033, SD = 0.032) exceeds the mean for width measurements (0.019, SD = 0.045) by 0.015, with a 95% confidence interval for this difference of [0.005, 0.025]. This statistically significant difference suggests the sheep bones at Skálholt exhibit distinctive dimensional characteristics, with length measurements showing larger positive log-ratio values than width measurements.

This dimensional pattern has important morphological implications that could indicate several phenomena. First, it may reflect differential growth responses to environmental conditions, as length dimensions are typically less affected by nutritional stress than width dimensions, which respond more readily to resource limitations. Second, this pattern could result from selective breeding for particular body conformations in these sheep. Third, the dimensional differences might reflect demographic composition within the flock, as males, females, and castrates exhibit different patterns of bone development in length versus width. Finally, these measurements could indicate specific adaptations to local environmental conditions in early modern Iceland, where sheep represented the primary livestock resource under increasingly marginal conditions.

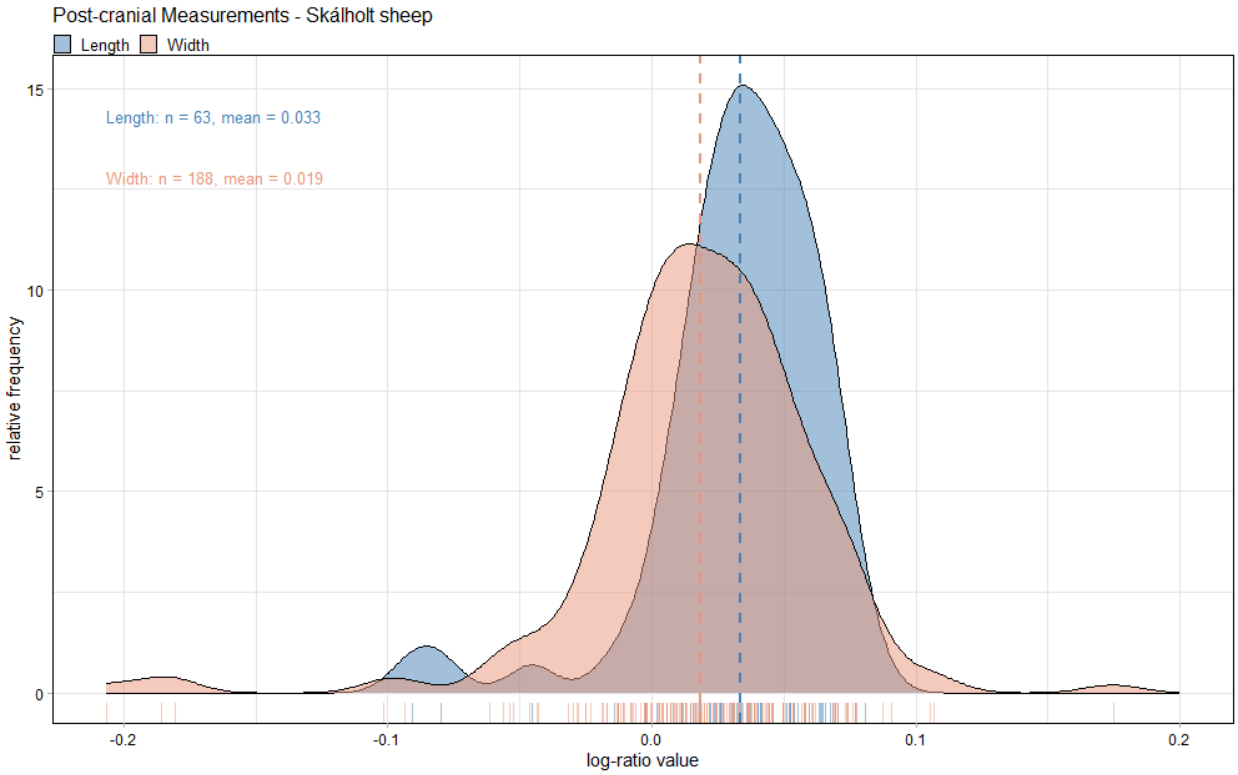

Figure 6.16. Post-cranial log-ratio measurements of Skálholt sheep by dimension. Length n = 63, mean = 0.033. Width n =188, mean = 0.019.

The distribution of measurements across skeletal elements shows clear patterns (Table 6.10). Width measurements are particularly well-represented in load-bearing bones, with the tibia (n = 55), humerus (n = 49), and radius (n = 34) providing the majority of the data. Length measurements, while fewer in number, are concentrated in the calcaneus (n = 22), metacarpal (n = 19), and metatarsal (n = 11). This distribution reflects both typical archaeological preservation patterns and the methodological constraints of taking different measurements on specific skeletal elements.

Table 6.10. Log-ratio length and width measurements for Skálholt sheep by element.

element	*n* length	*n* width
astragalus	0	10
calcaneus	22	0
metacarpal	19	21
metatarsal	11	16
phalanx 1	0	2
humerus	3	49
radius	5	34
femur	1	3
tibia	2	55
total *n*	63	190

Statistical testing illustrates some patterns in the Skálholt sheep bone measurements (Tables 6.11 and 6.12). The Shapiro-Wilk tests indicate that neither length ($W = 0.856$, $p < 0.001$) nor width ($W = 0.879$, $p < 0.001$) measurements follow a normal distribution, suggesting complexity in the underlying population structure. Levene's test for homogeneity of variance approaches but does not quite reach statistical significance ($F = 3.661$, $p = 0.057$), indicating marginally different variance patterns between length and width measurements. Given the non-normal distribution of both dimensions, a Wilcoxon rank sum test was conducted as the appropriate non-parametric alternative to the t-test. This analysis confirms a highly significant difference between length and width measurements ($W = 7557$, $p = 0.001$), with length values ($n = 63$, median = 0.037, mean = 0.033, SD = 0.032) consistently larger than width values ($n = 188$, median = 0.021, mean = 0.019, SD = 0.045). This marked difference in the lengths versus the widths suggests that the sheep assemblage at Skálholt might contain wethers or be representative of a heterogenous population of

multiple breeds of sheep, likely brought in from the surrounding farms, or, more likely, a combination of the two (Meadow 1999; Zeder and Lemoine 2020).

Table 6.11 Skálholt sheep summary statistics by element - Width log-ratio values.

element	*n*	mean	SD	median	Q1	Q3	min	max
astragalus (AST)	10	0.0177	0.0415	0.0120	-0.0066	0.0418	-0.0539	0.0906
calcaneus (CAL)	0							
metacarpal (MC)	21	0.0226	0.0298	0.0197	0.0110	0.0445	-0.0464	0.0740
metatarsal (MT)	16	0.0058	0.0224	0.0108	-0.0093	0.0212	-0.0318	0.0398
humerus (HUM)	49	0.0216	0.0334	0.0219	0.0027	0.0416	-0.0937	0.0874
radius (RAD)	34	0.0277	0.0357	0.0225	0.0072	0.0514	-0.0613	0.1070
femur (FEM)	3	0.0021	0.1034	0.0025	-0.0495	0.0539	-0.1014	0.1053
tibia (TIB)	55	0.0137	0.0619	0.0264	0.0013	0.0450	-0.2066	0.1746

Table 6.12 Skálholt sheep summary statistics by element - Length log-ratios values.

element	*n*	mean	SD	median	Q1	Q3	min	max
astragalus (AST)	0							
calcaneus (CAL)	22	0.0410	0.0219	0.0450	0.0270	0.0536	-0.0144	0.0810
metacarpal (MC)	19	0.0389	0.0222	0.0340	0.0209	0.0616	0.0021	0.0703
metatarsal (MT)	11	0.0217	0.0277	0.0304	0.0135	0.0362	-0.0454	0.0525
humerus (HUM)	3	-0.0396	0.0795	-0.0800	-0.0854	-0.0140	-0.0908	0.0520
radius (RAD)	5	0.0506	0.0256	0.0581	0.0412	0.0656	0.0111	0.0769
femur (FEM)	0							
tibia (TIB)	0							

The boxplots of sheep log-ratio measurements across different skeletal elements reveal some patterns in both width and length dimensions at Skálholt. The

width measurements demonstrate considerable variation between elements, with the most substantial sample sizes coming from major limb bones (humerus, radius, and tibia) (Figure 6.17). The metacarpal measurements (n = 21) display a relatively tight distribution with a median close to 0.02, suggesting consistent morphological characteristics across these elements. In contrast, metatarsals (n = 16) show a lower median value but with a similarly compact distribution. The radius elements (n = 34) present the highest median values among the well-represented elements, indicating relatively robust proximal limb articulations compared to the Soay reference standard.

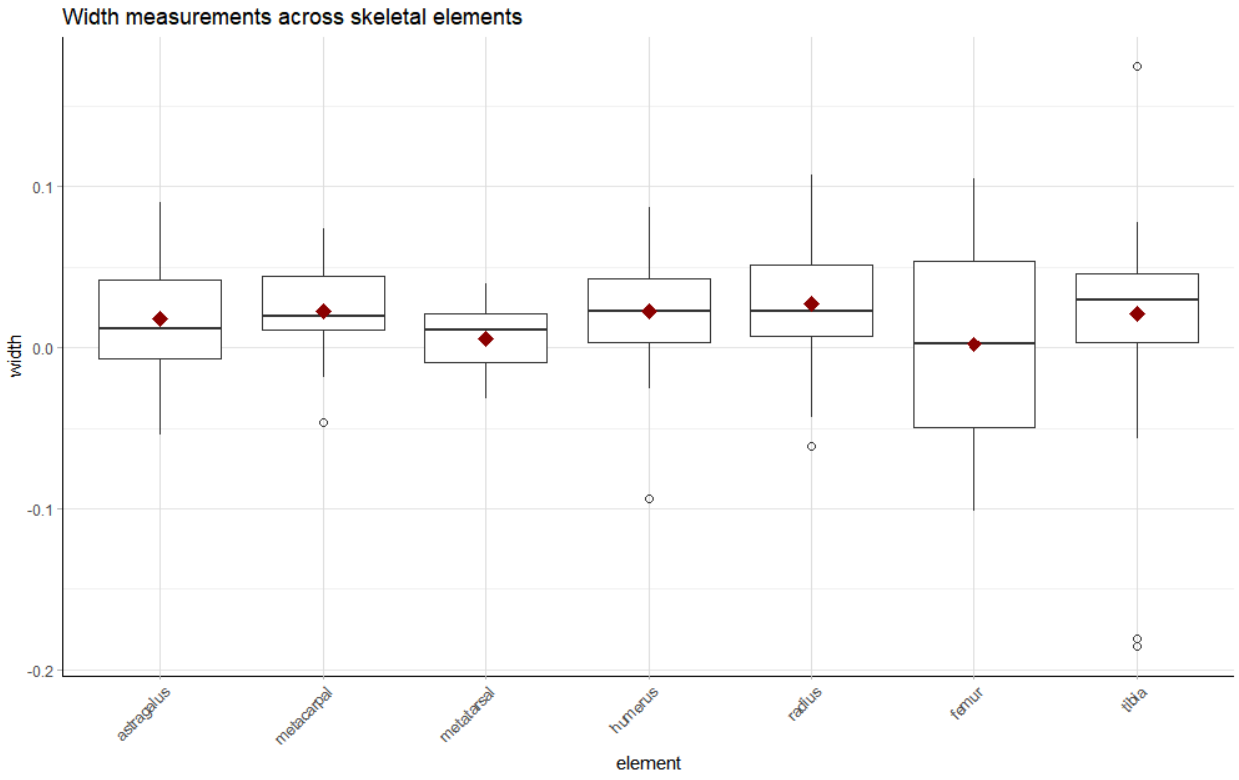

Figure 6.17. Width measurements across skeletal elements - Skálholt sheep.

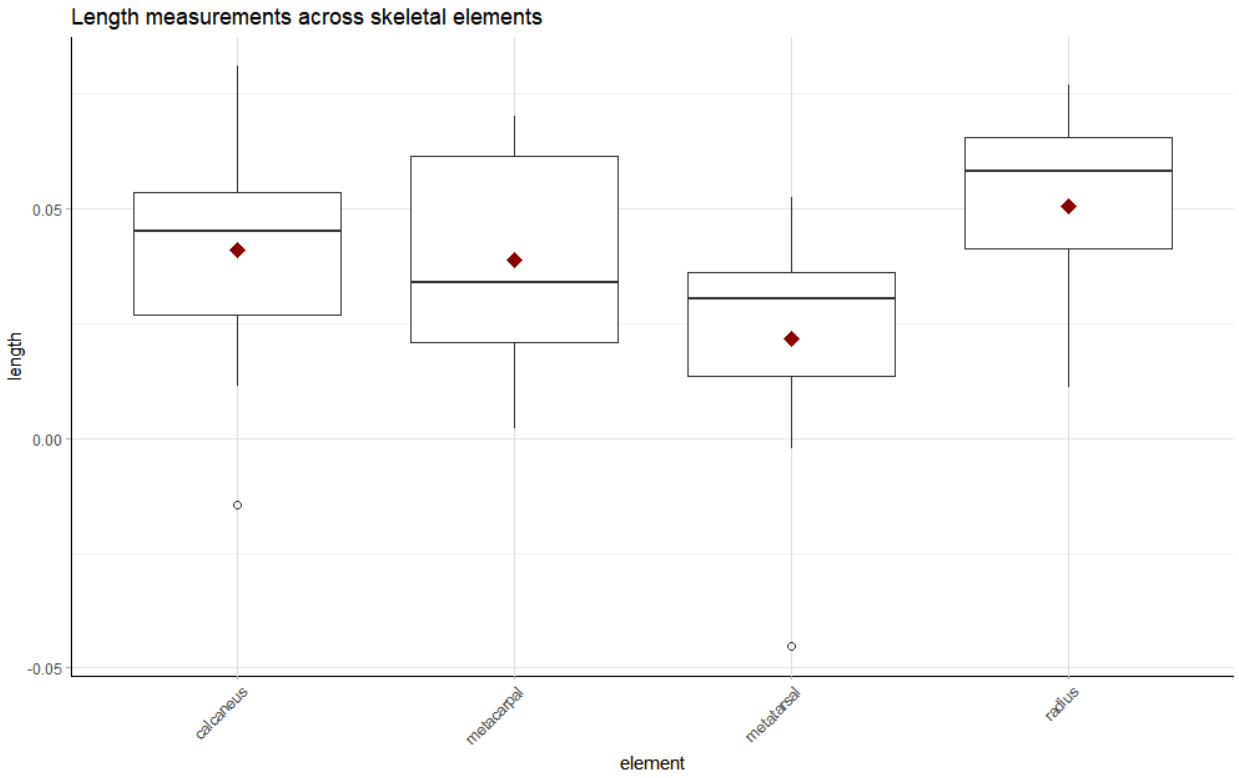

Figure 6.18. Length measurements across skeletal elements - Skálholt sheep.

The length measurements reveal an even more pronounced pattern of element-specific variation (Figure 6.18). Calcanei (n = 22) and metacarpals (n = 19) demonstrate consistently positive log-ratio values, with medians well above zero, suggesting these elements were substantially longer than the reference standard. The metatarsals (n = 11) show positive but more moderate values. This differential pattern between fore and hind limb elements, with metacarpals exhibiting greater positive deviation from the standard than metatarsals, could reflect specialized breeding or management practices. The radius measurements (n = 5), while few in number, demonstrate the highest positive values of any element, though their limited sample size necessitates cautious interpretation. Together, these patterns of dimensional

variation across different elements provide foundational evidence for examining specialized sheep husbandry practices at Skálholt, which will be explored in subsequent sections addressing questions of wether management and potential breeding improvements.

6.2.2 Skálholt Household vs. Midden

For an initial approach to the caprines of Skálholt, the log ratios of remains recovered from the major midden context (Midden Zone C) and interior locations identified as the dining room of the Bishop of Skálholt and a storeroom are compared against each other (Figure 6.19). The Household samples derive from a storeroom near the Bishop's dining area and other furnished rooms - a relatively more high-status space by 1698 (Lucas and Snæsdóttir 2022). In contrast, Midden Zone C represents a designated waste disposal area that accumulated domestic refuse, hearth sweepings, and butchery waste throughout the seventeenth and eighteenth centuries, providing a broader view of site-wide consumption patterns (Hambrecht 2011; Lucas and Snæsdóttir 2022).

The length measurements from the Household area (n = 20) show a mean log ratio of 0.033, while those from Midden Zone C (n = 25) have a nearly identical mean of 0.032. Width measurements demonstrate a larger sample size in both locations, with the Household area yielding 82 measurements (mean = 0.018) and Midden Zone C providing 109 measurements (mean = 0.024). The greater number of width measurements is largely due to the preservation of epiphyseal ends of long bones,

particularly the humerus, radius, and tibia, which provide multiple width measurements per element.

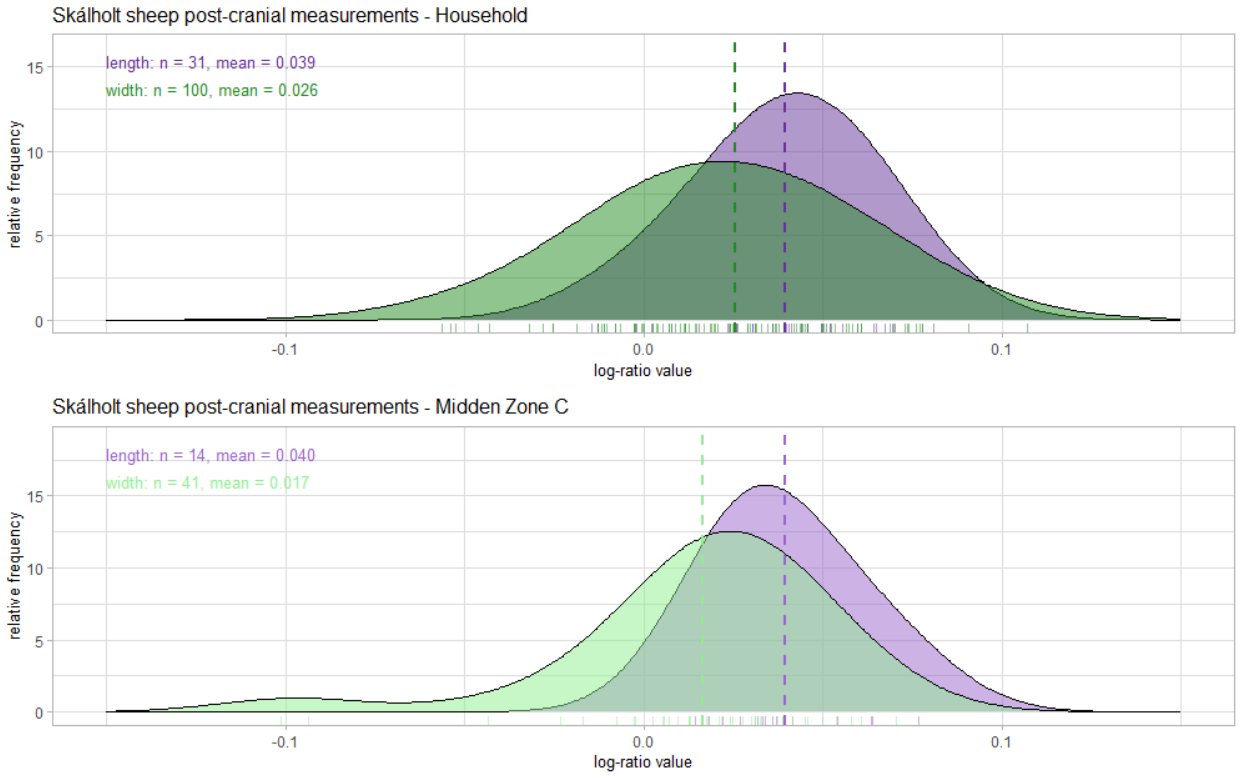

Figure 6.19. Skálholt post-cranial measurements for sheep by location.

The distribution of measurements varies between elements and locations. In the Household area, width measurements are particularly well-represented from the tibia (n = 27), humerus (n = 22), and radius (n = 15), while length measurements primarily come from the calcaneus and metacarpal. The Midden Zone C assemblage shows a similar pattern, with width measurements dominated by the tibia (n = 31), humerus (n = 27), and radius (n = 19), though it yielded more complete long bones providing length measurements from the metacarpal and metatarsal.

The Shapiro-Wilk tests for the length measurements indicate normal distributions in both locations (Household: $p = 0.747$; Midden Zone C: $p = 0.322$), with particularly strong normality in the Household data ($W = 0.978$). Levene's test confirms homogeneity of variances between the locations ($F = 0.989$, $p = 0.326$). The ANOVA results show no significant difference in lengths between the locations ($F(1, 43) \approx 0$, $p = 0.987$), with a negligible effect size ($\delta = -0.005$, 95% CI: [-0.654, 0.644]). The very low F value and the confidence interval crossing zero further support the lack of meaningful difference in length measurements between the two locations.

For the width measurements, both locations show significant departures from normality (Household: $p = 0.001$; Midden Zone C: $p < 0.001$) according to the Shapiro-Wilk tests. However, Levene's test indicates homogeneous variances ($F = 1.905$, $p = 0.170$). The ANOVA results reveal no significant difference in widths between the locations ($F(1, 139) = 1.588$, $p = 0.21$), despite a larger sample size compared to the length measurements (139 vs. 43 residual df). The effect size for the width comparison is small ($\delta = 0.234$, 95% CI: [-0.134, 0.601]), with the confidence interval crossing zero, suggesting an uncertain effect.

The strong positive correlation between length and width measurements, coupled with a significant p-value, indicates a consistent pattern of growth and shape in the sheep from both the Household and Midden Zone C loci. This uniformity suggests that the sheep were likely of the same breed and experienced similar environmental and nutritional conditions, resulting in consistent growth patterns and body proportions. Although the width measurements exhibit slightly more variation

and non-normal distributions compared to the length measurements, the differences between the locations remain non-significant and small in effect size.

6.2.3 Wethers and Breeding Improvements

The biometrical data from Skálholt's sheep assemblage provides evidence for both specialized husbandry practices and potential breed improvement during the seventeenth and eighteenth centuries. By examining metapodial measurements, particularly the relationship between length and width dimensions, we can identify distinctive morphological signatures that suggest the presence of castrates (wethers) and potentially differentiate them from intact males and females. Withers height estimates also provide insights into potential size increases that may reflect either selective breeding or improved management practices.

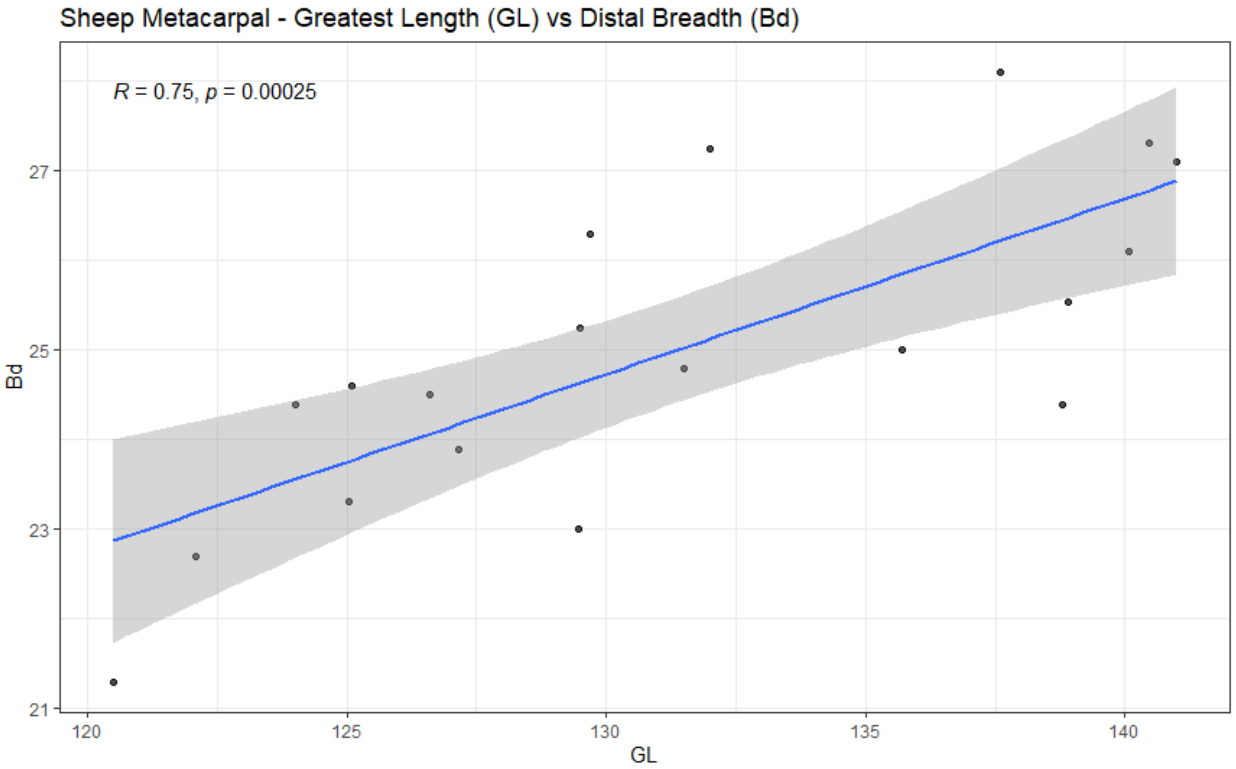

Figure 6.20. Scatterplot of Skálholt sheep metacarpal GL and Bd.

Metapodial Morphology and Slenderness Indices

Metacarpal measurements from Skálholt exhibit a particularly strong correlation between greatest length (GL) and distal breadth (Bd), with a Pearson's coefficient of 0.75 (p = 0.00025) (Figure 6.20). This high correlation suggests consistent growth patterns across the assemblage, where increases in bone length typically correspond with proportional increases in distal width (Popkin et al. 2012). The metatarsal measurements demonstrate a weaker correlation (R = 0.29, p = 0.38) (Figure 6.21), potentially indicating greater morphological variability in hind limb elements compared to forelimbs. When these measurements are plotted together (Figure 6.22), the differential relationship between length and width dimensions becomes more apparent, with metacarpals showing more consistent proportionality.

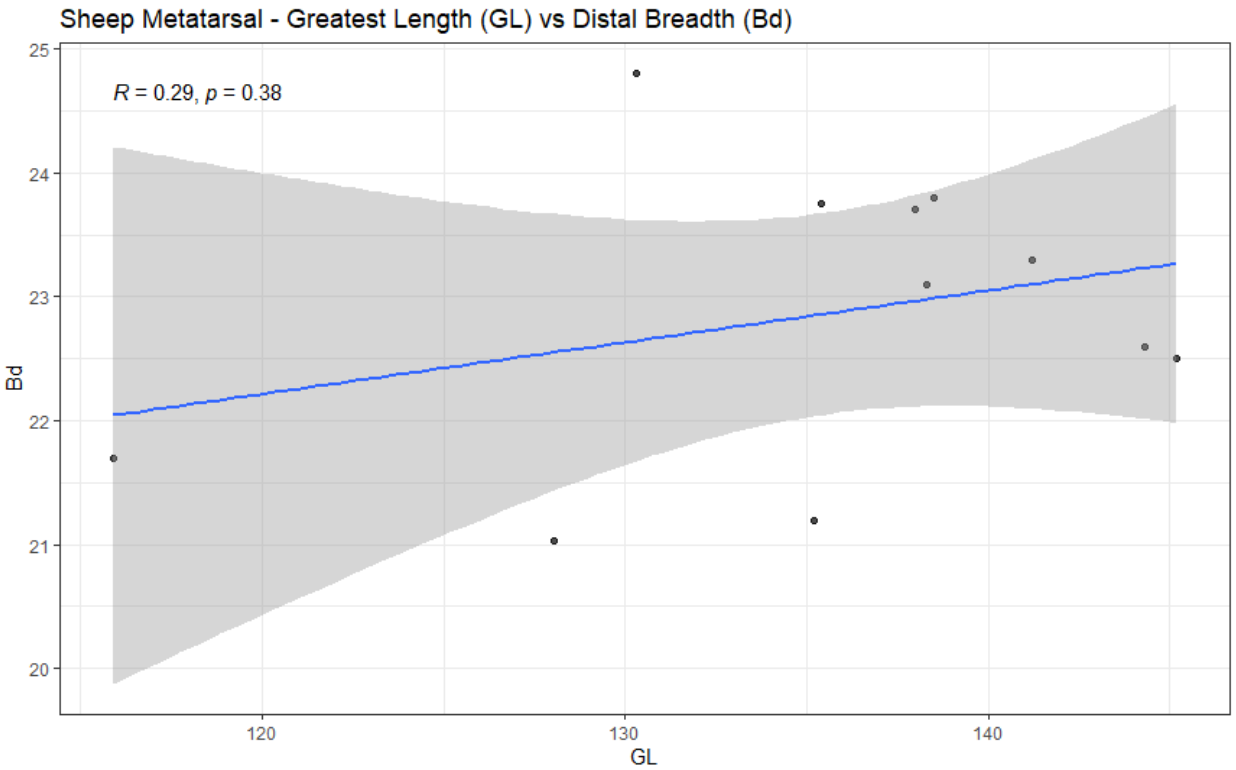

Figure 6.21. Scatterplot of Skálholt sheep metatarsal GL and Bd.

This distribution of specimens provides initial indications of potential wether presence in the assemblage. Following Davis (2000) and Popkin and colleagues (2012), we would expect females to cluster in the lower left quadrant (shorter, narrower bones), intact males in the upper right (longer, broader bones), and castrates in the upper left (longer but relatively narrow bones). While definitive categorization of individual specimens is challenging due to measurement overlap, the presence of several specimens in the upper left quadrant of the metacarpal plot (Figure 6.23) suggests the potential presence of wethers in the assemblage.

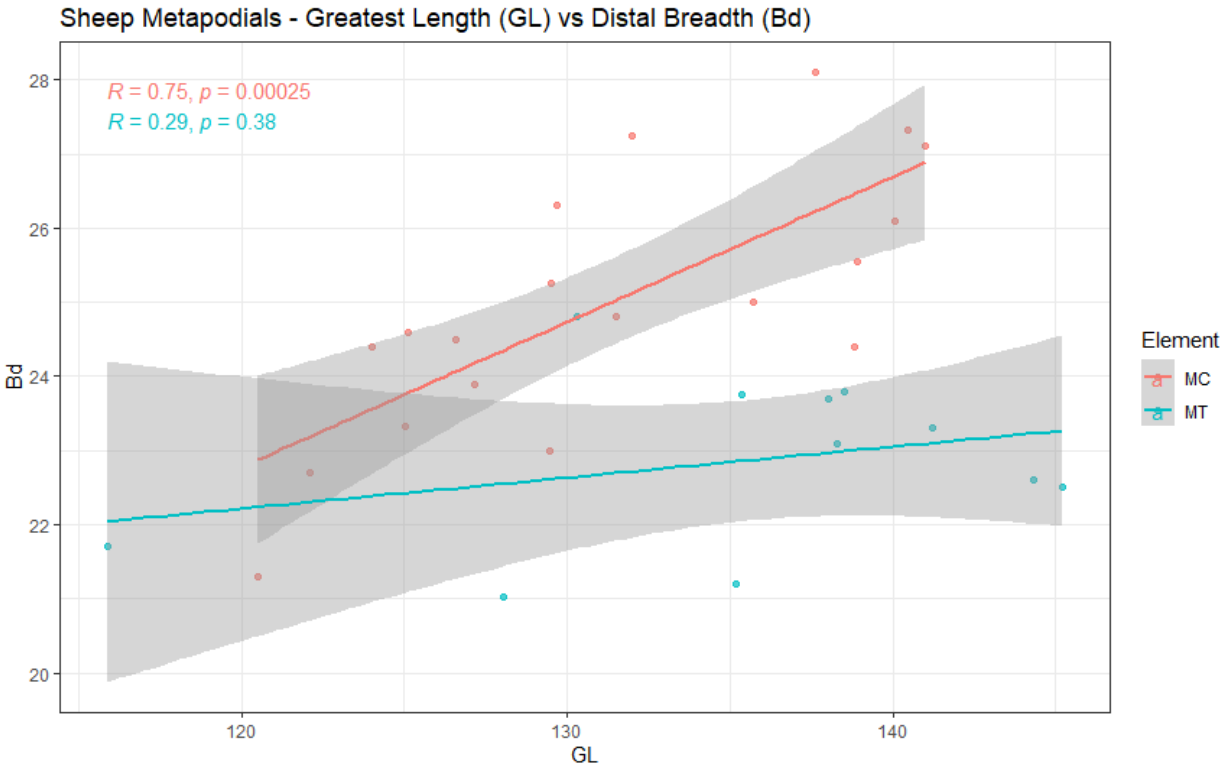

Figure 6.22. Scatterplot of Skálholt sheep metapodial GL and Bd.

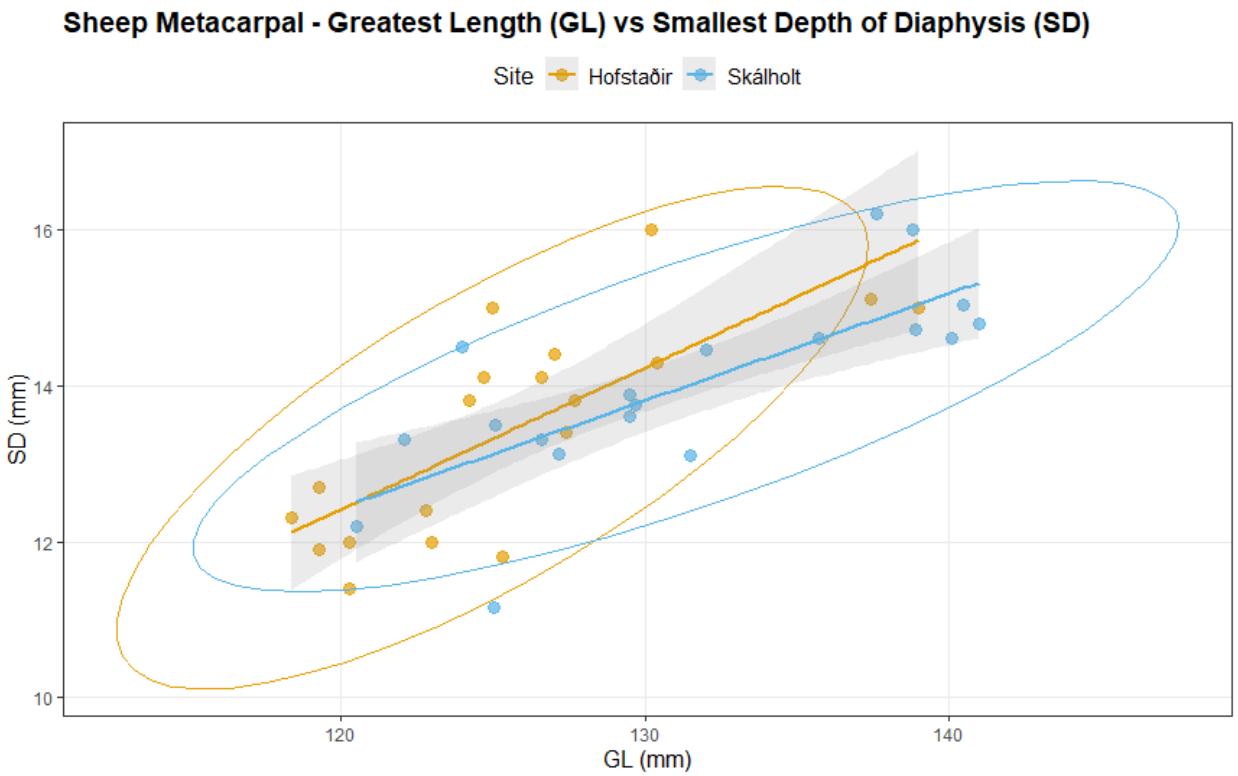

Figure 6.23. Ovis MC GL vs. SD from Skálholt and Hofstaðir. Confidence ellipses, regression lines with confidence intervals.

When Skálholt specimens are compared with metacarpal measurements from other Icelandic sites, several patterns emerge (Figure 6.24). The Skálholt specimens generally occupy the upper portion of the plot, indicating consistently longer metacarpals than those from Hofstaðir and Hrísheimar. Furthermore, the regression line for Skálholt specimens demonstrates a distinctive slope, reflecting a specific relationship between length and width dimensions that differs from that observed at the earlier sites. This pattern reinforces the suggestion that the Skálholt sheep may represent a modified population compared to earlier Icelandic assemblages, potentially reflecting either different breeding priorities or improved management practices.

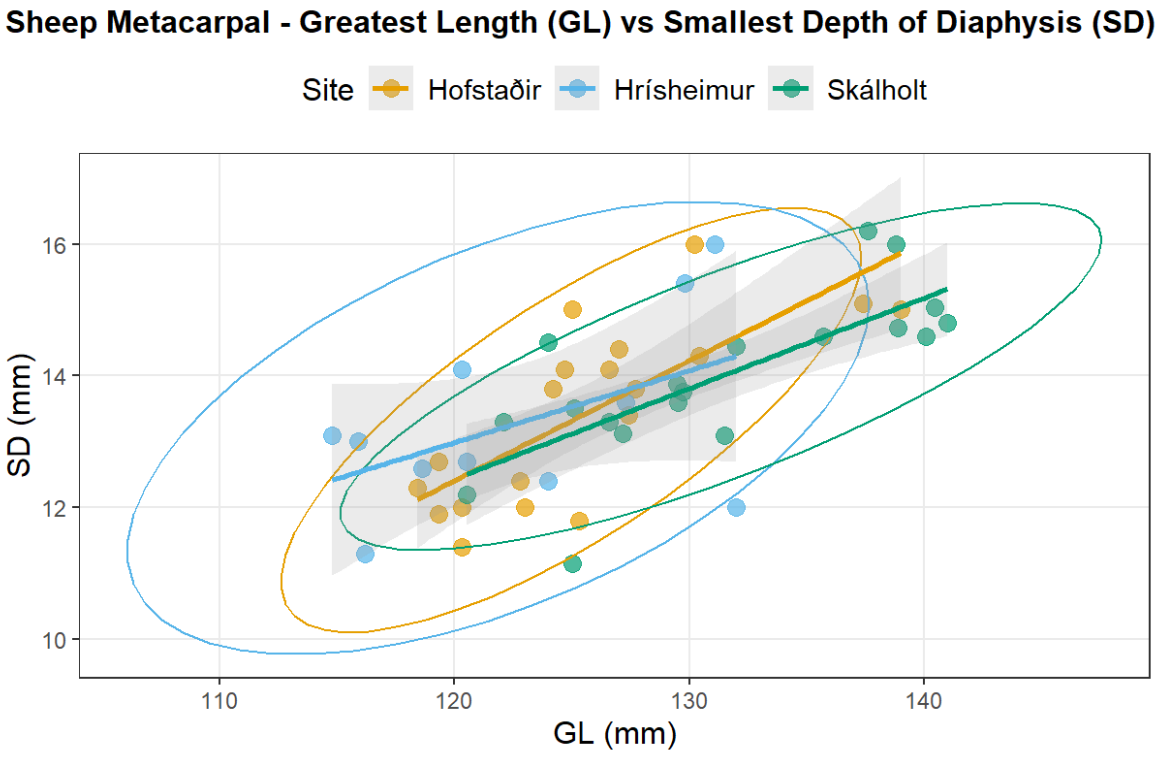

Figure 6.24. Ovis MC GL vs. SD from Skálholt, Hofstaðir, and Hrísheimar. Skálholt specimens generally display greater lengths while maintaining similar shaft diameters compared to earlier sites, suggesting morphological changes possibly related to wether management or selective breeding practices.

The slenderness index provides a more standardized approach to examining these relationships (Guintard and Lallemand 2003). Figure 6.25 compares slenderness indices across Skálholt, Hofstaðir, Hrísheimar, and Greenland's Western Settlement, highlighting some distinctive patterns for both metacarpals and metatarsals. For metacarpals, Western Settlement specimens demonstrate the highest mean slenderness index (12.3) with considerable variability (SD = 1.33), while Hofstaðir (10.7), Hrísheimar (10.8), and Skálholt (10.6) show remarkably similar mean values. Notably, Skálholt exhibits the lowest variability (SD = 0.636) among these sites,

suggesting a more standardized sheep population with more consistent morphological characteristics.

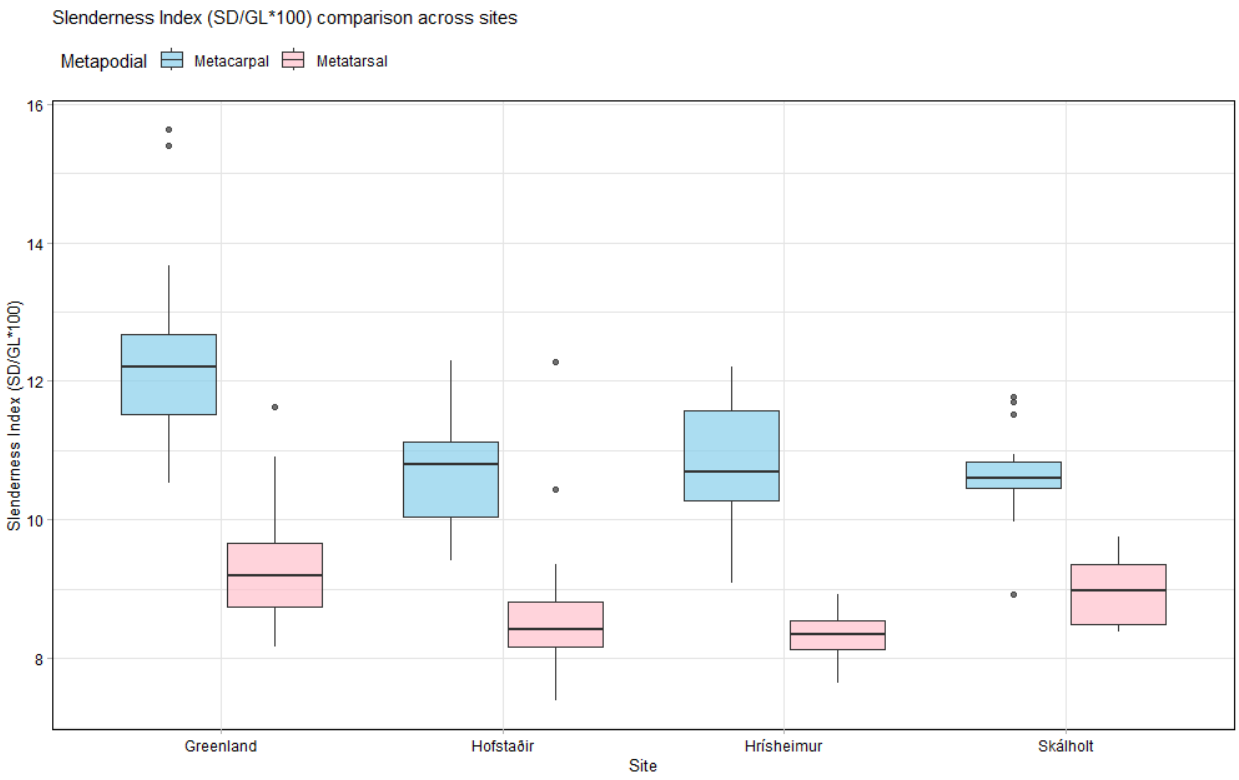

*Figure 6.25. Slenderness Index (SD/GL*100) comparison across sites - Sheep.*

The metatarsal slenderness indices show a different pattern, with the Western Settlement again demonstrating the highest values (9.35), followed by Skálholt (8.96), then Hofstaðir (8.62) and Hrísheimar (8.33). This decreasing differential suggests more proportional growth between fore and hind limbs in the Skálholt sheep, potentially indicating reduced sexual dimorphism, more consistent management practices, or selective breeding for specific body conformations. The smaller differential at Skálholt, combined with lower overall slenderness indices and

reduced variability, strongly suggests a more managed population with potentially different demographic composition than at earlier sites.

Figure 6.26 further explores these relationships, focusing specifically on metacarpal slenderness indices with potential wether identification. The distribution pattern indicates the presence of at least some wethers in the Skálholt assemblage, particularly specimens falling in the lower ranges of the slenderness index distribution while maintaining relatively long overall dimensions. This pattern aligns with expectations for castrated males based on reference data from modern Shetland sheep (Davis 2000), where wethers develop longer but more slender bones compared to intact males due to delayed epiphyseal fusion coupled with reduced shaft diameters.

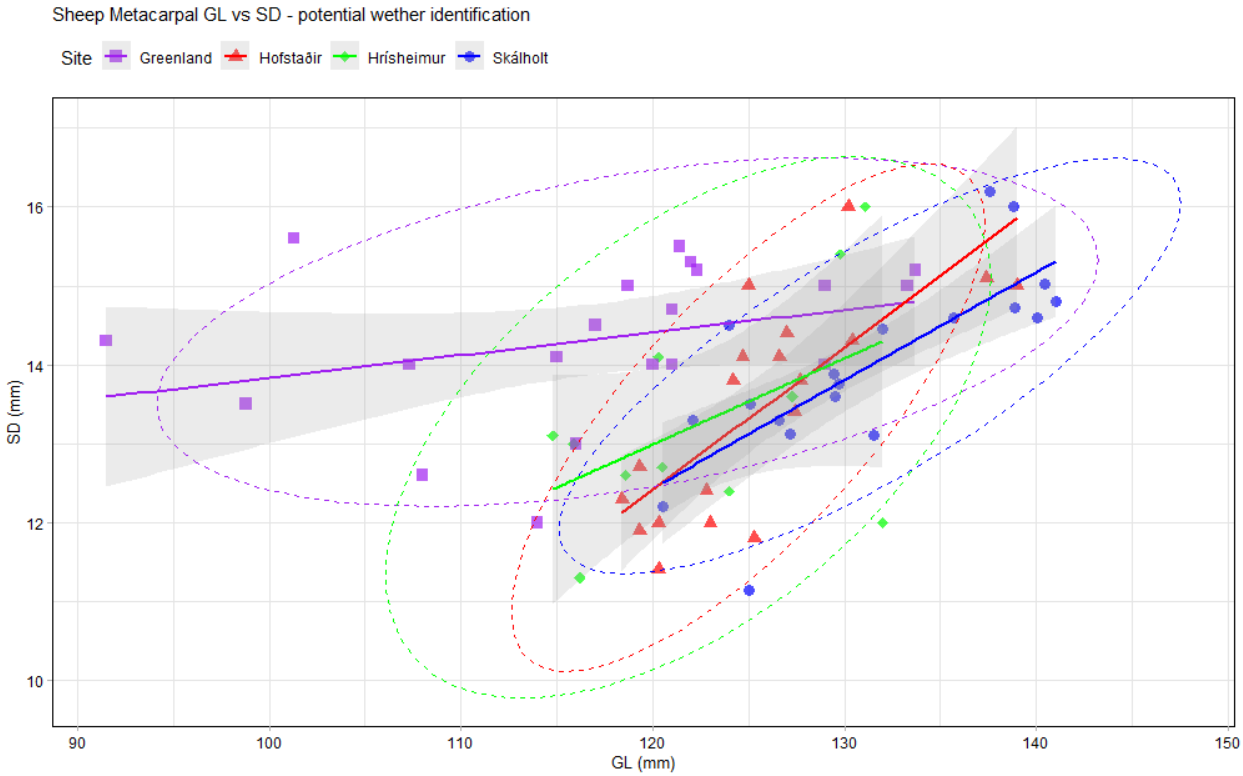

Figure 6.26. Sheep metacarpal GL vs. SD – potential wether identification. Relatively long metacarpals but comparatively narrow shaft diameters (lower slenderness indices), particularly in the Skálholt assemblage, is a morphological signature consistent with delayed epiphyseal fusion patterns documented in wethers.

Withers Height Reconstruction

Withers height estimations provide additional evidence for potential differences in the Skálholt sheep compared to other Icelandic assemblages. As shown in Table 6.13 and Figure 6.27, Skálholt sheep demonstrate the tallest estimated heights based on metacarpal measurements (mean = 64.22 cm), exceeding those from Hofstaðir (61.47 cm), Hrísheimar (60.04 cm), and Sveigakot (60.27 cm) by substantial margins. These differences – 2.75 cm taller than Hofstaðir, 4.18 cm taller than Hrísheimar, and 7.25 cm taller than specimens from the Western Settlement (56.97 cm) – represent statistically significant variations that exceed normal population variability.

Table 6.13. Stature reconstruction for sheep.

site	element	*n*	min	max	mean	sd
Sveigakot	MC	28	55.62	69.62	60.27	3.1411
	MT	30	56.95	69.96	63.28	3.5061
Hrísheimar	MC	11	56.14	64.55	60.04	3.1256
	MT	10	56.52	69.05	60.37	3.9942
Hofstaðir	MC	19	57.90	67.97	61.47	2.7725
	MT	29	54.34	68.74	60.98	3.7796
Steinbogi	MT	1	65.83	65.83	65.83	
Gásir	MC	1	63.33	63.33	63.33	
	MT	2	62.20	99.29	80.74	26.2279
West Settlement	MC	23	44.74	65.38	56.97	5.6717
	MT	18	48.44	69.46	58.52	4.8914
Möðruvellir	MC	2	61.61	63.23	62.42	1.1411
	MT	3	60.56	67.19	62.86	3.7507
Skálholt	MC	19	58.92	68.95	64.22	3.2785
	MT	11	52.62	65.92	61.51	3.7823
Old Scatness	MC	10	51.74	58.68	55.84	2.5328
	MT	5	51.62	66.69	58.38	5.3964

Metatarsal-based withers height estimates show less dramatic differences, with Skálholt (61.51 cm) and Hofstaðir (60.98 cm) exhibiting similar means, while Hrísheimar (60.37 cm) and Western Settlement (58.52 cm) demonstrate progressively smaller dimensions. This pattern of greater differences in metacarpal-derived estimates compared to metatarsal-derived estimates further supports the potential presence of wethers, as castration typically affects metacarpal growth more substantially than metatarsal development (Davis 2000; Popkin et al. 2012).

The similarity in cattle dimensions between Hofstaðir and Skálholt, despite their temporal separation, may reflect their shared institutional contexts as centers with substantial social and sacred obligations. Both sites functioned as locations where large numbers of people gathered for religious, administrative, and social purposes, necessitating more consistent and perhaps specialized livestock management practices. While Hofstaðir served as a high-status site with potential pre-Christian ritual functions in the Viking Age, Skálholt operated as Iceland's principal ecclesiastical center during the early modern period. These parallel institutional roles – both requiring the provisioning of significant numbers of people beyond immediate household members – might have driven similar cattle management strategies despite their different chronological contexts. This functional similarity could explain why these sites demonstrate more comparable morphological patterns in cattle than might be expected given their temporal distance, suggesting that institutional responsibilities may have influenced livestock management decisions as significantly as environmental constraints or technological capabilities.

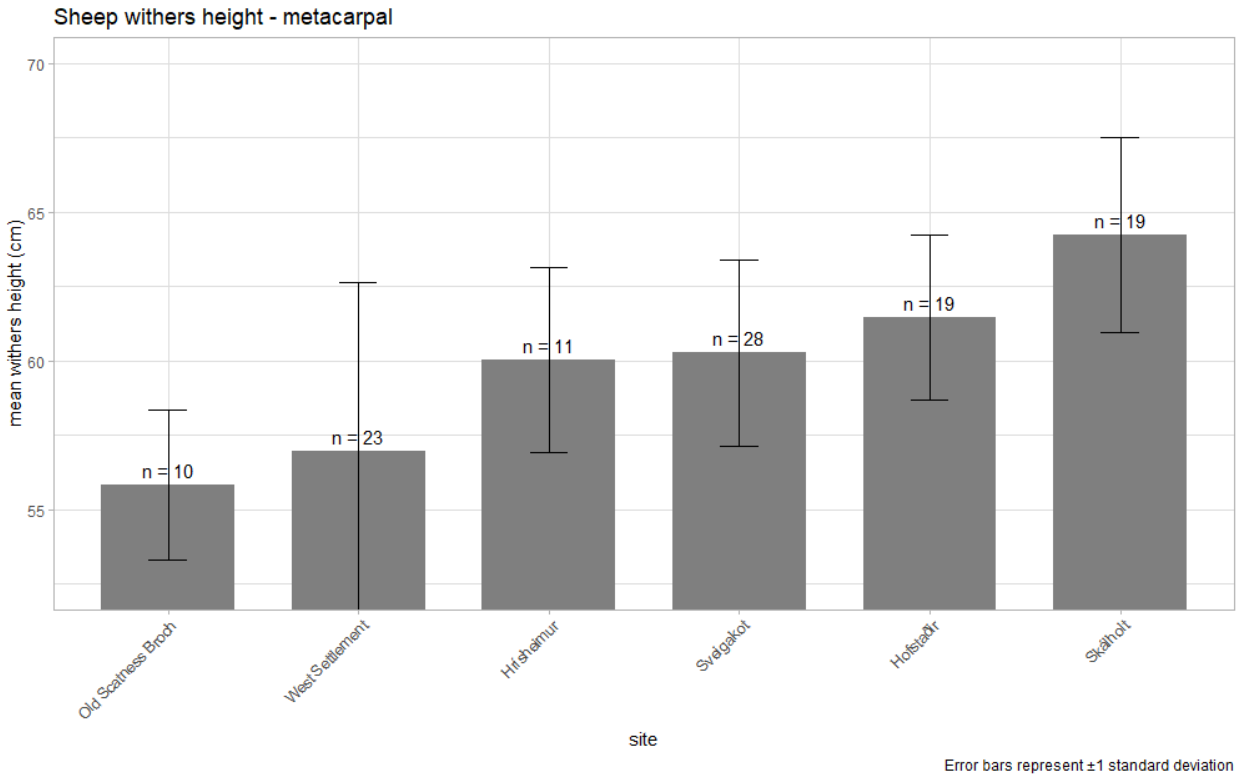

Figure 6.27. Sheep withers height - metacarpal.

Bimodality testing using Hartigans' dip test (p = 0.232) indicates no statistically significant bimodality in the Skálholt metacarpal withers height distribution. However, mixture analysis suggests the potential presence of two components within the population: a primary group comprising approximately 69% of animals with a mean height of 62.45 cm, and a secondary group comprising about 31% of animals with a mean height of 68.2 cm. This pattern could indicate a demographically mixed population, potentially consisting of ewes and wethers, or alternatively, might suggest the presence of multiple breed types within the assemblage.

The metacarpal ratio provides additional insight into potential castration effects. Skálholt specimens demonstrate the highest ratio (1.04) compared to Hofstaðir (1.01), Hrísheimar (0.994), and Western Settlement (0.974). This higher

ratio at Skálholt further supports the potential presence of wethers, as castration typically affects metacarpal growth more significantly than metatarsal growth, resulting in disproportionately longer forelimbs.

Documentary sources indicate that wethers were specifically maintained for wool production, with their more consistent fleece quality and higher wool yields (Ingimundarson 1995). The biometrical evidence suggesting a substantial wether population at Skálholt corresponds with the site's economic role and administrative function, where livestock management would have been particularly sophisticated.

The taller stature of Skálholt sheep compared to earlier Icelandic assemblages raises questions about potential breed improvement or introduction. While the increasing height might suggest the introduction of larger European breeds, several factors indicate this more likely represents improvement through selective breeding and enhanced management practices:

- The dimensional increase appears more substantial in length measurements than in width measurements, a pattern consistent with wether-focused husbandry rather than fundamental breed changes.
- The reduced variability in slenderness indices suggests standardized management rather than mixed breed introduction, which would typically increase measurement variability.
- The historical context of the seventeenth-eighteenth centuries aligns with documented agricultural improvement efforts at Skálholt, including barley cultivation (Hambrecht 2011, 2012).

Rather than wholesale breed replacement, the evidence more strongly supports selective breeding within the established Icelandic sheep population, focusing on

animals with desired characteristics – particularly larger body size and potentially enhanced wool production. This interpretation aligns with broader European agricultural improvement movements during this period, though adapted to Iceland's specific environmental constraints and resource limitations.

The morphological patterns observed in the Skálholt sheep assemblage provide compelling evidence for specialized management practices during the seventeenth and eighteenth centuries. The combination of consistently longer metacarpals, reduced slenderness indices with lower variability, taller estimated withers heights, and higher metacarpal ratios collectively supports three key interpretations.

First, the metapodial dimensions strongly suggest a substantial wether component within the Skálholt flock. The distinctive pattern of longer but relatively slender metacarpals aligns with documented effects of castration on bone development (Davis 2000; Popkin et al. 2012), where delayed epiphyseal fusion allows continued longitudinal growth while hormonal changes reduce shaft diameter. The significantly higher withers heights at Skálholt compared to earlier Icelandic sites further supports this interpretation, as wethers typically develop taller stature than ewes. This management strategy makes economic sense for an elite ecclesiastical center where wool production would have been a significant priority (Róbertsdóttir 2014).

Second, the reduced variability in slenderness indices at Skálholt compared to other sites indicates more standardized management practices. While earlier sites like Sveigakot, Hrísheimar, and Hofstaðir show considerable measurement variability,

suggesting mixed husbandry strategies, Skálholt's more consistent patterns point toward deliberate selection and specialized management (McGovern et al. 2009). This standardization aligns with Skálholt's documented administrative capacity and economic resources, which would have facilitated more controlled breeding and management regimes than were possible at smaller farms.

Third, the biometrical evidence suggests potential selective breeding for increased stature, though not necessarily through the introduction of new breeds. The consistently taller withers heights at Skálholt (metacarpal mean = 64.22 cm) compared to earlier sites like Hofstaðir (61.47 cm) and Hrísheimar (60.04 cm) indicate a meaningful size increase that exceeds typical population variability. However, the pattern of this increase – more pronounced in length than width measurements and with reduced overall variability – suggests enhancement through selective breeding within the established Icelandic population rather than wholesale breed replacement (Thomas et al. 2013; Wright and Viner-Daniels 2015).

These findings situate Skálholt within the broader context of early modern agricultural developments while highlighting distinctively Icelandic adaptations. Rather than directly mimicking English agricultural improvement models, which focused heavily on dramatic size increases through breed introductions (Grau-Sologestoa and Albarella 2019), Skálholt's approach appears more calibrated to Iceland's environmental constraints and economic priorities. This selective adaptation of improvement concepts—enhancing specific productive characteristics while maintaining adaptations to local conditions—represents a sophisticated response to both European influences and Icelandic realities.

The bimodality analysis provides additional nuance to this picture. Although Hartigans' dip test ($p = 0.232$) indicates no statistically significant bimodality in withers height distribution, the mixture analysis suggesting two potential population components (69% with mean height of 62.45 cm; 31% with mean height of 68.2 cm) potentially reflects the demographic composition of ewes and wethers rather than distinct breeds. This pattern aligns with specialized wool production strategies where wethers would be maintained alongside breeding ewes, with the larger group likely representing the female breeding stock.

These morphological patterns correlate with broader agricultural developments in early modern Europe while demonstrating regionally specific adaptations. The evidence suggests that Skálholt participated in the wider currents of agricultural innovation during this period but adapted these concepts to Iceland's particular environmental and economic context through selective enhancement of existing stock rather than wholesale breed replacement (Zeder 2015; Zeder and Lemoine 2020).

6.2.4 Comparison to Medieval Icelandic Sheep

The biometrical analysis of sheep from Skálholt provides an opportunity to examine potential morphological changes in Icelandic livestock between the Viking Age/medieval period and the early modern era. By comparing Skálholt's sheep measurements with those from earlier settlements like Sveigakot, Hofstaðir, and Hrísheimar, as well as specialized sites like Gásir and Möðruvellir, we can investigate whether Skálholt's assemblage demonstrates evidence of breed improvement, trade

connections, or environmental adaptation. This section examines these comparative relationships through both length and width measurements across multiple skeletal elements to answer three key questions: Were Skálholt sheep larger than earlier specimens? Do they demonstrate connections with trading centers? Or do they show evidence of nutritional stress?

Increased Dimensions: Evidence for Breeding Improvement

The dimensional comparison between Skálholt sheep and those from earlier Icelandic sites reveals compelling evidence for size increase, particularly in length measurements. Skálholt sheep demonstrate significantly taller withers heights based on metacarpal measurements (mean = 64.22 cm) compared to earlier sites including Hofstaðir (61.47 cm), Hrísheimar (60.04 cm), and Sveigakot (60.27 cm). These substantial differences – 2.75 cm taller than Hofstaðir, 4.18 cm taller than Hrísheimar, and 3.95 cm taller than Sveigakot – represent statistically significant variations that exceed normal population variability (Figure 6.28).

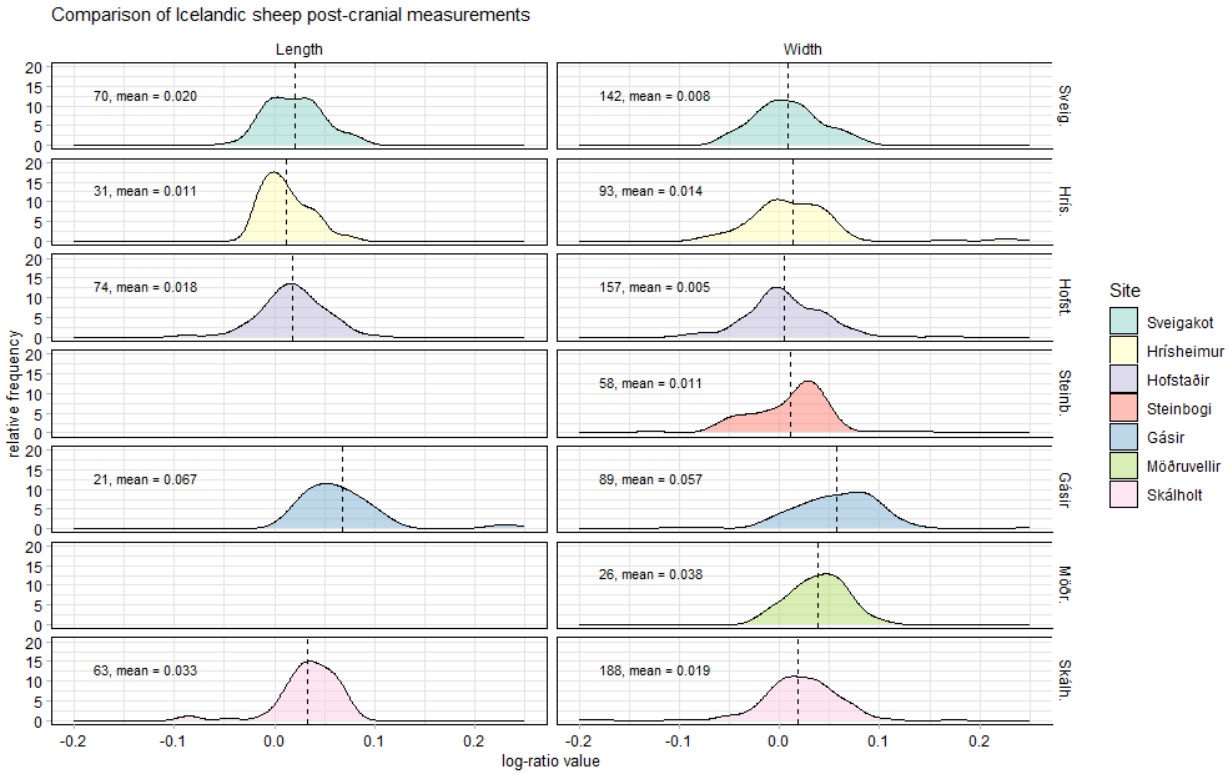

Figure 6.28. Comparison of sheep post-cranial measurements at Icelandic sites by length and width.

The log-ratio analysis of sheep length measurements confirms this pattern, with Skálholt specimens (mean = 0.033) showing significantly larger values than both Hrísheimar (mean = 0.011, p = 0.0004) and Hofstaðir (mean = 0.018, p = 0.0047). This dimensional increase, most pronounced in metacarpal measurements, suggests potential selective breeding for increased stature at Skálholt during the early modern period. Importantly, the pattern of dimensional change – more substantial in length than width measurements – indicates improvement through selective breeding within the established Icelandic population rather than wholesale breed replacement or introduction.

Note regarding Skálholt versus Sveigakot measurements: While withers height reconstructions show Skálholt sheep were taller than those from Sveigakot (64.22 cm vs. 60.27 cm), the log-ratio analysis indicates that Sveigakot had larger log-ratio values for length ($p = 0.0095$). This apparent discrepancy reflects the different analytical approaches: withers heights are calculated from raw measurements, while log-ratios express the relationship to a standardized reference specimen (in this case, Soay sheep). Both metrics are valid but address different aspects of morphological variation.

The density plots of metacarpal measurements across four Icelandic sites illustrate a chronological pattern in both length and width dimensions (Figure 29). For length measurements, Skálholt specimens demonstrate substantially larger dimensions (mean = 0.039) compared to earlier sites, with Hofstaðir (mean = 0.020), Hrísheimar (mean = 0.010), and Sveigakot (mean = 0.011) showing progressively smaller values. This pattern indicates a significant dimensional increase in metacarpal length between the medieval and early modern periods. Notably, the distribution for Skálholt exhibits a distinctive bimodal pattern, with peaks around 0.02 and 0.07, suggesting the presence of two morphologically distinct groups within the assemblage. This bimodality aligns with expectations for a mixed population of ewes and wethers, as castration typically produces elongated metacarpals through delayed epiphyseal fusion (Davis 2000; Popkin et al. 2012).

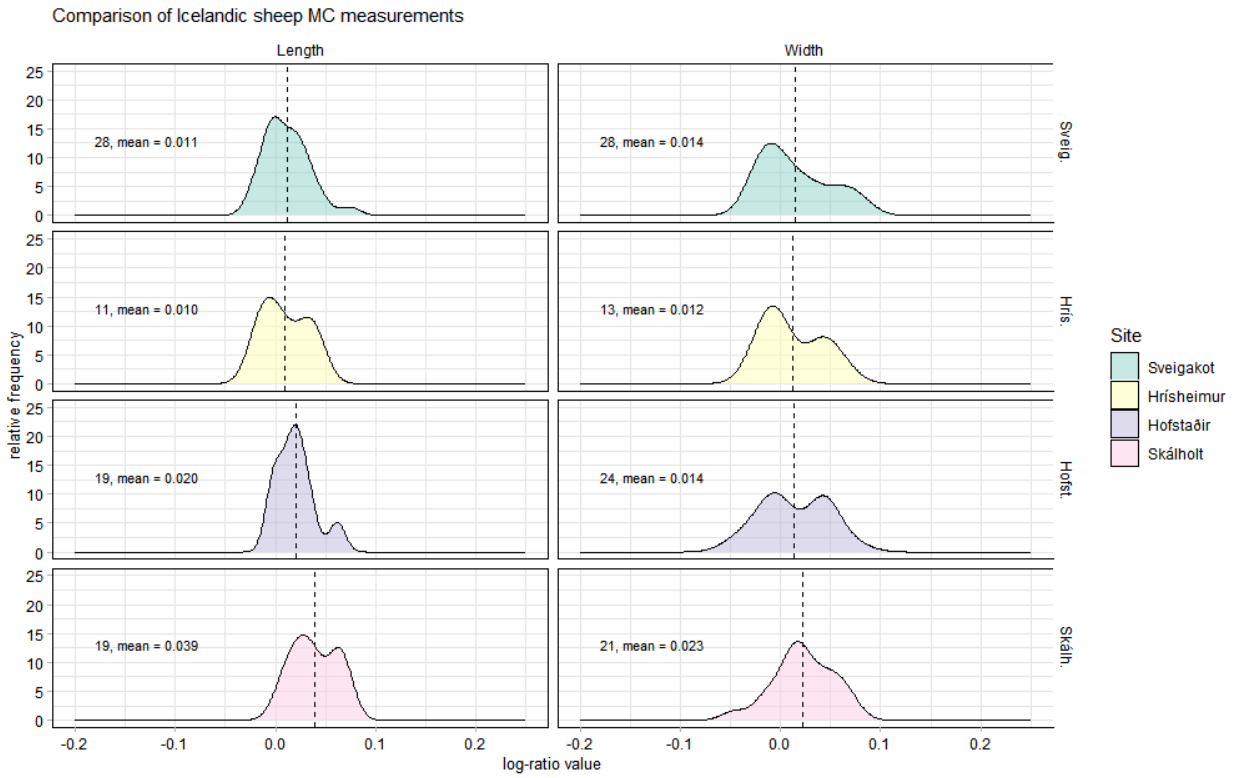

Figure 6.29. Log-ratio measurements of sheep metacarpals (MC) from four Icelandic sites.

Metacarpal width measurements show a similar but less pronounced chronological pattern, with Skálholt (mean = 0.023) exhibiting larger dimensions than the earlier sites of Hofstaðir (mean = 0.014), Hrísheimar (mean = 0.012), and Sveigakot (mean = 0.014). The smaller relative increase in width compared to length dimensions at Skálholt is particularly informative, as it indicates a shift toward more slender proportions despite overall size increase. This pattern aligns with expectations for specialized wether management focused on wool production, where castrates typically develop longer but more slender bones compared to intact males (Popkin et al. 2012).

The substantial wether component identified in the Skálholt assemblage reflects a management strategy primarily focused on wool production rather than optimizing meat yields. Documentary evidence from Iceland indicates that wether-focused husbandry represents a deliberately inefficient approach to meat production (Ingimundarson 1995). Wethers typically reach their maximum carcass weight by their third summer, yet historical sources indicate they were often maintained until seven or eight years of age before culling – a practice that significantly reduces overall meat production efficiency. This management approach directly competed with opportunities to maintain larger breeding flocks for both reproduction and milk production, suggesting that Skálholt's sheep management prioritized wool quality and quantity over maximizing meat yields or dairy products. The slaughter of older wethers at the end of their productive wool-bearing lives would provide meat as a secondary product, but the biometrical evidence suggesting substantial wether presence indicates a production system structured around wool as the primary economic objective. This specialized focus aligns with Skálholt's documented role within regional economic networks, where woolen products represented crucial commodities for both ecclesiastical revenues and broader trade systems during the Danish Trade Monopoly period.

The metatarsal density plots also illustrate interesting contrasts with the metacarpal patterns (Figure 6.30). For length measurements, Sveigakot unexpectedly shows the highest mean value (0.034), followed by Skálholt (0.022), Hofstaðir (0.018), and Hrísheimar (0.013). This reversal of the expected chronological pattern, where the earliest site (Sveigakot) demonstrates larger dimensions than the latest site

(Skálholt), suggests differential selection pressures or management practices affecting fore and hind limbs across these settlements. The width measurements show less variation across sites, with Sveigakot (mean = 0.014) exceeding both Skálholt (mean = 0.006) and Hofstaðir (mean = 0.007), while Hrísheimar shows the lowest values (mean = 0.002).

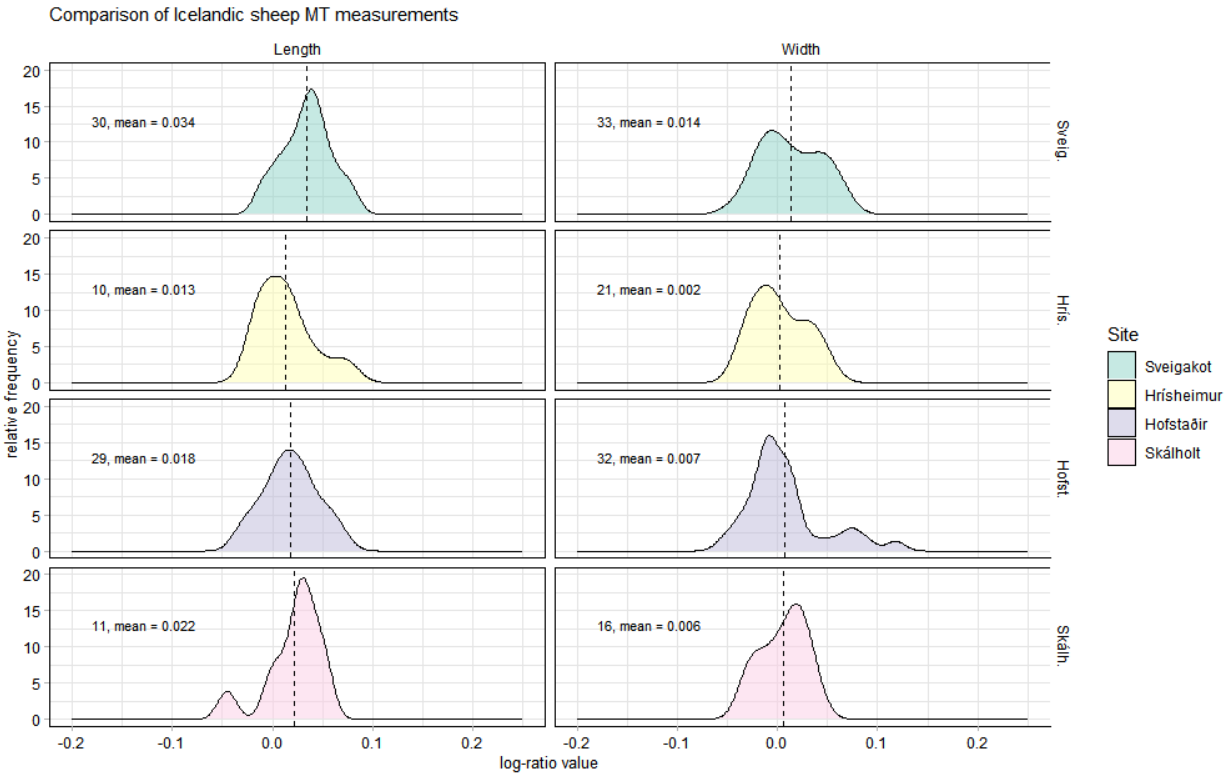

Figure 6.30. Log-ratio measurements of sheep metatarsals (MT) from four Icelandic sites.

The contrasting patterns between metacarpals and metatarsals are suggestive of several implications for specialized livestock management. The substantially larger increase in metacarpal versus metatarsal length at Skálholt suggests deliberate selection for animals with distinctive forelimb proportions, potentially reflecting

specialized wool production strategies focused on wether maintenance. Davis (2000) observed differential effects of castration on fore and hind limbs in Shetland sheep, with metacarpals showing more pronounced elongation than metatarsals following castration. The bimodal distribution of metacarpal length measurements at Skálholt, coupled with the more unimodal distribution of metatarsal measurements, further supports the interpretation that these patterns reflect sex-based morphological differences rather than simply chronological change or environmental adaptation. The distinctive proportion of metacarpal to metatarsal dimensions at Skálholt thus indicates evidence for specialized livestock management strategies at this elite ecclesiastical center during the early modern period.

Relationship to Trading Centers: Distinct from Gásir and Möðruvellir

While Skálholt sheep demonstrate increased dimensions compared to earlier settlement sites, they remain significantly smaller than specimens from specialized economic centers, particularly Gásir and Möðruvellir. The medieval trading center at Gásir exhibits the largest sheep measurements across all Icelandic sites examined, with exceptionally high log-ratio values for both length (mean = 0.067) and width (mean = 0.057) (Figure 28). Möðruvellir similarly shows elevated dimensions (length mean = 0.045; width mean = 0.039), likely reflecting its established provisioning relationship with Gásir and its status as a high-ranking ecclesiastical establishment (Harrison 2007, 2008).

The substantial dimensional difference between these specialized sites and Skálholt (length mean = 0.033; width mean = 0.019) indicates that despite its elite

ecclesiastical status, Skálholt maintained sheep populations with distinctive morphological characteristics rather than directly emulating patterns observed at trading centers. Statistical testing confirms significant differences between Skálholt and both Gásir and Möðruvellir, suggesting that each type of establishment developed specialized livestock management strategies aligned with their particular economic roles and environmental contexts.

This pattern suggests that while Skálholt likely engaged with broader trade networks and agricultural innovations, its sheep management strategies were adapted to local conditions and specific institutional needs rather than directly replicating practices from specialized trading centers or earlier settlements. The intermediate position of Skálholt's sheep measurements between early settlement sites and specialized trade centers potentially reflects its distinctive role as an ecclesiastical center balancing multiple economic priorities.

Dimension Differentials: Length vs. Width Patterns

A particularly informative aspect of this comparative analysis is the differential pattern between length and width measurements across sites. At Skálholt, sheep bones demonstrate greater positive deviation from the reference standard in length measurements (mean = 0.033) than in width measurements (mean = 0.019), with this difference being statistically significant ($p = 0.00502$) (Tables 6.14 and 6.15). This pattern – more pronounced increases in length than width – represents a distinctive morphological signature with important interpretive implications.

Table 6.14. Summary statistics for Icelandic sheep log-ratio width measurements.

site	*n*	mean	SD	min	max	distribution	significance
Sveigakot	142	0.008	0.033	-0.059	0.083	normal	smaller than GAS, MOD, SKL
Hrísheimar	93	0.014	0.048	-0.077	0.231	non-normal	smaller than GAS, MOD
Hofstaðir	157	0.005	0.042	-0.207	0.165	non-normal	smaller than GAS, MOD, SKL
Steinbogi	58	0.011	0.042	-0.128	0.140	non-normal	smaller than GAS, MOD
Gásir	89	0.057	0.046	-0.110	0.246	non-normal	significantly larger than all but MOD
Möðruvellir	26	0.039	0.027	-0.015	0.097	normal	larger than HOF, HRI, SVK
Skálholt	188	0.019	0.045	-0.207	0.175	non-normal	larger than HOF, SVK

First, this differential pattern aligns with the expected morphological effects of castration, where delayed epiphyseal fusion allows continued longitudinal growth without corresponding increases in bone width (Davis 2000; Popkin et al. 2012). The combination of significantly increased metacarpal length with relatively moderate width increases strongly suggests a substantial wether component within the Skálholt flock, a management strategy that would align with documented wool production priorities at ecclesiastical centers (Ingimundarson 1995).

Second, the pattern contrasts with what would be expected from simple nutritional enhancement, which typically affects width dimensions more substantially than length dimensions (Pálsson and Vergés 1952a, b). The greater increases in length than width suggest genetic selection rather than merely improved nutrition, further supporting the hypothesis of deliberate breeding strategies at Skálholt.

When comparing this dimensional pattern across sites, Skálholt's assemblage demonstrates a distinctive signature that differs from both early settlement sites and specialized trading centers. While sites like Gásir show substantial increases in both length and width dimensions, Skálholt exhibits a more differentiated pattern

suggesting specialized management practices focused on particular morphological traits rather than simple size maximization.

Table 6.15. Summary statistics for Icelandic sheep log-ratio length measurements.

site	*n*	mean	SD	min	max	distribution	significance
Sveigakot	70	0.020	0.028	-0.044	0.086	normal	significantly smaller
Hrísheimar	31	0.011	0.023	-0.019	0.073	non-normal	significantly smaller
Hofstaðir	74	0.018	0.031	-0.088	0.096	normal	significantly smaller
Steinbogi	7*	0.050	0.037	0.013	0.128	normal	no significant difference
Gásir	21	0.067	0.045	0.022	0.230	non-normal	significantly larger
Möðruvellir	6*	0.045	0.040	0.016	0.118	non-normal	no significant difference
Skálholt	63	0.033	0.320	-0.091	0.081	non-normal	intermediate

Management and Environmental Factors: Evidence Against Nutritional Stress

The biometrical evidence strongly counters the hypothesis that Skálholt sheep show size decrease consistent with nutritional stress. Several lines of evidence support this conclusion:

First, the consistently larger dimensions of Skálholt sheep compared to earlier settlement sites, particularly in length measurements, directly contradict expectations for populations experiencing nutritional limitation. Under nutritional stress, both length and width dimensions would typically show reduction, with width dimensions often exhibiting more pronounced decreases (Pálsson and Vergés 1952a). The observed pattern at Skálholt – increased length measurements with moderate width increases – suggests enhanced rather than diminished resource access.

Second, the reduced variability in slenderness indices at Skálholt compared to other sites indicates more standardized management practices rather than

environmental stress. While earlier sites show considerable measurement variability suggesting mixed husbandry strategies, Skálholt's more consistent patterns point toward deliberate selection and specialized management. This standardization aligns with Skálholt's administrative capacity and economic resources, which would potentially have facilitated more controlled breeding and management regimes than were possible at smaller farms.

Third, the historical context of Skálholt as a wealthy ecclesiastical center with substantial landholdings supports the interpretation of enhanced rather than stressed management conditions. The bishopric's access to extensive grazing lands, fodder resources, and labor would have enabled sophisticated husbandry practices that could mitigate environmental limitations and maintain consistent livestock quality despite broader environmental challenges (Hambrecht 2011; Júlíusson et al. 2020; Lucas and Snæsdóttir 2022).

Chronological Trends: Changes in Sheep Morphology Across Icelandic History

When situated within broader chronological patterns, Skálholt's sheep assemblage provides valuable insights into the evolution of livestock management in Iceland from settlement through the early modern period. The biometrical patterns suggest several key transitions in sheep morphology over time:

Early settlement sites (ninth-eleventh centuries) like Sveigakot, Hrísheimar, and Hofstaðir show considerable variability in sheep measurements, reflecting diverse management strategies during the initial adaptation to Iceland's environment

(McGovern et al. 2009). This variability likely represents the demographic diversity of founding populations and the experimental nature of early husbandry practices.

By the medieval period, specialized economic sites like Gásir (thirteenth-fifteenth centuries) demonstrate substantial increases in sheep dimensions, likely reflecting selective provisioning or specialized production strategies aligned with commercial priorities (Harrison 2009). The significantly larger sheep at these trading centers suggest the emergence of more specialized economic networks with differentiated livestock management practices.

Skálholt's early modern assemblage (seventeenth-eighteenth centuries) represents a distinctive phase in this chronological development, showing moderate size increases compared to settlement-period sites but with different dimensional patterns than specialized trading centers. This suggests an evolving approach to sheep management that incorporated aspects of both traditional practices and innovative strategies.

This chronological pattern indicates that sheep morphology in Iceland did not follow a simple linear trajectory of either improvement or degradation. Rather, it reflects complex interactions between environmental conditions, economic priorities, and management strategies that varied across different site types and time periods. Skálholt's distinctive position in this pattern suggests that elite ecclesiastical centers maintained specialized approaches to livestock management that balanced traditional adaptations with selective innovations aligned with their particular institutional needs.

Summary and Implications. The comparative analysis of sheep measurements across Icelandic sites reveals that Skálholt maintained a distinctive livestock population during the seventeenth-eighteenth centuries that demonstrates significant morphological differences from both earlier settlement sites and specialized trading centers. The evidence strongly supports several key conclusions:

First, Skálholt sheep were significantly larger than those from settlement-period sites, particularly in length measurements, suggesting the potential deliberate breeding for increased stature. However, this improvement appears to have occurred through selective breeding within the established Icelandic population rather than wholesale breed replacement.

Second, while Skálholt sheep show evidence of improvement, they maintain distinctive morphological characteristics that differ from specialized trading centers like Gásir, suggesting adaptation to local conditions and institutional needs rather than simple emulation of external models.

Third, the dimensional patterns at Skálholt strongly counter the hypothesis of nutritional stress, instead indicating standardized management practices consistent with the site's elite ecclesiastical status and extensive economic resources.

These findings situate Skálholt within the broader context of early modern agricultural developments while highlighting distinctively Icelandic adaptations. Rather than directly mimicking external agricultural models, Skálholt's approach appears calibrated to Iceland's environmental constraints and the specific economic priorities of a major ecclesiastical center. This selective adaptation of improvement concepts – enhancing specific productive characteristics while maintaining

adaptations to local conditions – represents a sophisticated response to both European influences and Icelandic realities during a period of significant agricultural transition.

6.2.5 Regional Adaptation: Sheep Morphology Across the North Atlantic

The comparative analysis of sheep morphology can be extended beyond Iceland to include broader North Atlantic contexts, providing valuable insights into regional patterns of adaptation and management. By incorporating data from the Norse settlements in Greenland and Old Scatness in Shetland, we can examine how sheep populations in these distinctive insular environments compare to those in Iceland, including Skálholt. This expanded comparative framework enables investigation of how environmental factors, cultural practices, and potential genetic isolation may have influenced livestock morphology across different North Atlantic settings during roughly contemporaneous periods.

Dimensional Patterns Across North Atlantic Regions

Statistical analysis of sheep postcranial measurements (Figure 6.31) reveals significant morphological differences between regions, with distinctive patterns for both length and width dimensions. Kruskal-Wallis testing demonstrates highly significant differences in length measurements across the three regions ($\chi^2 = 35.56$, df = 2, $p < 0.001$), with post-hoc Dunn's tests confirming significant differences between all paired comparisons (Greenland-Iceland: $p = 0.0004$; Greenland-Shetland: $p < 0.0001$; Iceland-Shetland: $p = 0.0001$). The effect sizes for these comparisons are substantial (rank-biserial correlations: Greenland-Iceland = 1.31; Greenland-Shetland

= 1.58; Iceland-Shetland = 1.38), indicating meaningful morphological differentiation between regional populations.

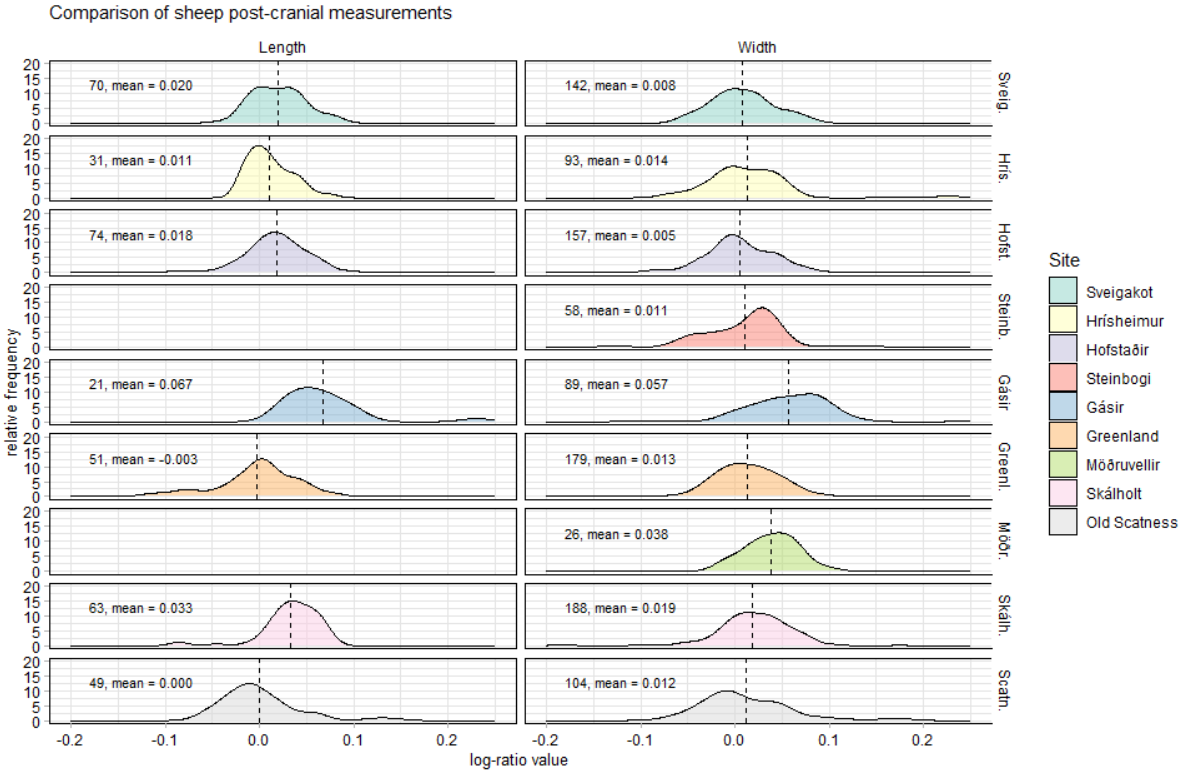

Figure 6.31. Comparison of sheep post-cranial measurements across the North Atlantic by length and width.

Width measurements show a similar but less pronounced pattern of regional differentiation (Kruskal-Wallis: $\chi^2 = 10.67$, df = 2, p = 0.0048). Post-hoc testing reveals significant differences between Greenland and Shetland (p = 0.0020) and marginally significant differences between Greenland and Iceland (p = 0.0379), while Iceland and Shetland do not differ significantly (p = 0.0689). These differential patterns between length and width measurements suggest complex interactions

between genetic factors and environmental conditions across the North Atlantic region.

When examining specific site-level data, several intriguing patterns emerge. Greenlandic sheep exhibit significantly larger dimensions (mean = 0.0303) than Old Scatness specimens (mean = 0.0001), with Icelandic sites occupying an intermediate position (mean = 0.0191). This pattern is particularly pronounced in length measurements, which typically show greater resistance to nutritional stress than width dimensions. The substantial dimensional advantage of Greenland sheep contradicts expectations based on environmental marginality, as Greenland represented the most environmentally challenging of these North Atlantic settlements with the shortest growing seasons and most limited grazing resources (Cussans 2017; McGovern 1985).

Adaptation and Selection in Greenland

The unexpectedly larger dimensions of Greenlandic sheep, particularly evident in length measurements, suggest several possible interpretations with significant implications for understanding Norse adaptation strategies in this marginal environment. First, the larger dimensions could reflect deliberate selection for more robust animals during the initial settlement of Greenland, potentially representing a "founder effect" where colonists preferentially transported larger, hardier livestock to this challenging new environment (McGovern et al. 2014). This selective process would align with documentary evidence suggesting that Greenlandic settlement was

more carefully planned than the earlier Icelandic colonization, with deliberate resource selection for the new colony (Arneborg et al. 2012).

Second, the larger dimensions could reflect adaptive responses to the distinctive environmental conditions of Greenland's Western Settlement. In particular, the extreme seasonality of Greenland's maritime climate, with its extended darkness in winter and continuous daylight in summer, creates distinctive growth patterns that might favor greater overall body size during the peak growth season (McGovern 1985) The combination of continuous summer daylight and relatively abundant summer forage during the short growing season could potentially support accelerated growth during this period, despite the extreme winter constraints that necessitated extended indoor housing.

Third, the larger Greenlandic sheep dimensions may reflect more intensive management strategies necessitated by environmental constraints. Historical and archaeological evidence indicates that Greenlandic Norse farmers maintained smaller overall herd sizes than their Icelandic counterparts but invested more intensively in their care, including extended indoor stabling during the prolonged winter period (Dugmore et al. 2012; McGovern 2000). This intensive management, including selective winter feeding of priority animals, might have supported larger overall dimensions despite the marginal environment.

Island Dwarfism at Old Scatness

The consistently smaller dimensions of sheep from Old Scatness in Shetland (length mean = 0.0001; width mean = 0.0116) align with expectations for long-established insular populations. The dimensional patterns at this site, with mean values close to zero (indicating minimal deviation from the Soay reference standard), suggest minimal morphological change from primitive northern short-tailed sheep morphotypes like the Soay (Clutton-Brock et al. 1990; Ryder 1983). This pattern is consistent with the biogeographical principle of island dwarfism, where genetically isolated populations on islands frequently exhibit size reduction compared to mainland counterparts (Marshall and Corruccini 1978).

The Old Scatness assemblage spans the post-medieval to crofting periods (seventeenth-nineteenth centuries AD), representing a long-established sheep population adapted to Shetland's distinctive environmental conditions (Dockrill 2013). The small dimensions of these sheep align with historical documentation of Shetland breed characteristics, which emphasized hardiness, wool quality, and adaptation to marginal grazing conditions rather than body size (Cussans 2010). Despite being roughly contemporaneous with the Skálholt assemblage, these sheep show dramatically different morphological characteristics, highlighting the divergent pathways of sheep management and adaptation across different North Atlantic environments.

The lack of significant difference in width measurements between Shetland and Icelandic sheep, despite significant differences in length measurements, may reflect similar constraints on body robusticity imposed by nutritional limitations in

these insular environments. While length dimensions show greater influence from genetic factors, width dimensions more readily reflect nutritional status, suggesting similar resource constraints despite different genetic histories and management strategies (Pálsson and Vergés 1952a, b).

Skálholt's Position in the North Atlantic Context

When situated within this broader North Atlantic framework, Skálholt's sheep assemblage occupies a distinctive intermediate position that reflects both its environmental context and its specialized institutional role. While statistically grouped with other Icelandic sites in regional comparisons, Skálholt sheep demonstrate dimensional characteristics that distinguish them from both the larger Greenlandic specimens and the smaller Shetland sheep. The mean log-ratio values for Skálholt (length = 0.0303; width = 0.0220) exceed the overall Icelandic means (length = 0.0191; width = 0.0165), suggesting that this ecclesiastical center maintained relatively large sheep compared to the Icelandic average.

This intermediate position reinforces the interpretation that Skálholt represents a specialized adaptive strategy within the Icelandic context, balancing local environmental adaptation with institutional priorities for wool and meat production. The contrast with Shetland sheep is particularly instructive, as both assemblages date to roughly similar periods (seventeenth-nineteenth centuries AD), but demonstrate dramatically different morphological characteristics. While Shetland sheep maintained primitive dimensions closely aligned with the Soay reference standard,

Skálholt's assemblage shows evidence of deliberate enhancement, particularly in length measurements.

The significantly lower dimensions of Skálholt sheep compared to Greenlandic specimens, despite Iceland's generally more favorable environmental conditions, suggests that factors beyond simple environmental determination shaped these regional morphological patterns. The contrast highlights how cultural factors, including management priorities, institutional structures, and economic objectives, interacted with environmental conditions to produce distinctive regional adaptations across the Norse North Atlantic.

Patterns of Variation Across the North Atlantic

Analysis of variation patterns across the North Atlantic sheep populations here requires particular methodological consideration. In many biometrical analyses, coefficients of variation (standard deviation/mean*100) are used. However, examination of the standard deviations themselves provides more a reliable view into population variability than coefficients of variation (CV) in these zooarchaeological contexts. The use of CV values is particularly problematic when means approach zero, as occurs with the Old Scatness measurements. When mean values are extremely small (as in the Shetland assemblage where length mean = 0.0001), traditional CV calculations become mathematically unstable and produce disproportionately large values that obscure rather than clarify comparative patterns.

The standard deviations themselves reveal informative patterns of variation across regions. For length measurements, all three regions demonstrate similar

absolute variability (Iceland SD = 0.0378; Greenland SD = 0.0400; Shetland SD = 0.0406). This consistency in absolute variation despite significantly different mean values suggests multiple factors may be influencing population structures across these regions. Several likely explanatory factors must be considered here:

Environmental plasticity likely plays a role in shaping variability within each regional sheep population. Ross and colleagues (2016) note that North Atlantic in different environmental contexts often display similar ranges of responsiveness to factors like seasonal nutritional fluctuations and grazing pressure despite differences in baseline morphology. While Greenlandic sheep developed larger overall dimensions, their capacity to respond morphologically to environmental fluctuations appears comparable to smaller Shetland sheep, resulting in similar absolute variation ranges.

The genetic diversity profiles of regional populations may also contribute to this pattern. While the mean dimensions differ between regions, each population may maintain similar levels of genetic variability that support comparable morphological ranges despite different average sizes. The founder populations in these different North Atlantic settlements likely carried similar genetic diversity despite potentially different selection criteria during colonization.

Additionally, environmental constraints in marginal North Atlantic environments may create inherent limits on viable size ranges, regardless of average dimensions. As Ross and colleagues (2016) note, sheep grazing across the North Atlantic region has shaped landscapes and biodiversity while adapting to distinct environmental challenges. These constraints could produce similar absolute variation

ranges despite different mean values as sheep populations respond to the boundaries of viability in these marginal environments.

The similarity in absolute variation across regions with significantly different mean values has important implications for understanding livestock management strategies. Rather than indicating random variation, these patterns suggest that sheep populations across the North Atlantic were managed through approaches that maintained consistent phenotypic ranges while focusing on different target morphologies that suited local environmental conditions and economic priorities.

Regional Morphology and Adaptive Strategies

The comparative analysis of sheep morphology across the North Atlantic reveals distinctive regional patterns that reflect complex interactions between environmental conditions, cultural practices, and adaptive strategies. The larger dimensions of Greenlandic sheep challenge simplistic environmental determinism, suggesting that Norse settlers implemented specialized management strategies to maintain robust livestock in this marginal environment. The smaller dimensions of Shetland sheep align with biogeographical principles of island adaptation and documented breed characteristics emphasizing hardiness over size. Icelandic sheep, including those from Skálholt, occupy an intermediate position that reflects both environmental adaptation and diverse management priorities across different site types and time periods.

These regional patterns suggest that sheep morphology in the North Atlantic reflect not simple environmental determination, but complex adaptive strategies

shaped by cultural priorities, environmental limitations, and economic objectives. While all three regions maintained sheep populations adapted to insular environments, each developed distinctive morphological characteristics aligned with particular adaptive strategies. Greenland's emphasis on intensive management of small, high-quality herds maintained for meat and milk; Shetland's focus on hardiness and wool quality in small-bodied animals; and Iceland's diverse approaches ranging from specialized production at sites like Gásir and Skálholt to subsistence strategies at ordinary farms all produced identifiable morphological signatures in the archaeological record (Mainland 2006; McGovern et al. 2014; Worley et al. 2016).

Skálholt's position within this regional framework reinforces its interpretation as a site of specialized livestock management, where elite status and institutional resources supported distinctive management approaches. While maintaining sheep adapted to Icelandic conditions, Skálholt demonstrates evidence of deliberate enhancement that distinguishes it from both ordinary Icelandic farms and the primitive morphology preserved in contemporaneous Shetland populations.

6.2.6 Sheep Summary

The biometrical analysis of Skálholt's sheep assemblage provides substantive evidence for distinctive livestock management practices at this elite ecclesiastical center during the early modern period. The dimensional patterns revealed through multiple analytical approaches – including log-ratio scaling, withers height estimation, and slenderness indices – collectively demonstrate that Skálholt maintained sheep populations with morphological characteristics that distinguished

them from both earlier Icelandic assemblages and contemporaneous populations across the North Atlantic. The consistently larger dimensions of Skálholt sheep compared to earlier settlement sites, particularly in length measurements, suggest deliberate enhancement through selective breeding within established Icelandic populations rather than wholesale breed replacement. This pattern aligns with the historical evidence for agricultural innovation at Skálholt, including Björn Halldórsson's agricultural manual and barley cultivation (Halldórsson 1948, in Hambrecht 2011).

The distinctive relationship between length and width dimensions, with greater increases in length than width compared to reference standards, strongly indicates specialized management practices focused on wether production for wool. This interpretation is further supported by the reduced variability in slenderness indices at Skálholt compared to other sites, suggesting standardized management practices consistent with the site's documented administrative capacity and economic resources. When situated within the broader North Atlantic context, Skálholt's assemblage occupies an intermediate position between the larger Greenlandic specimens and smaller Shetland populations, highlighting the complex interplay between environmental adaptation and institutional priorities in shaping livestock morphology.

These findings suggest that Skálholt represents not simply emulation of English agricultural improvement models but rather a distinctive Icelandic engagement with broader currents of agricultural innovation, calibrated to local environmental constraints and institutional needs. The evidence for selective

enhancement within established populations, standardized management practices, and specialized production strategies demonstrates sophisticated adaptation of improvement concepts within Iceland's marginal environment. This regionally specific approach to agricultural innovation, balancing traditional adaptations with selective enhancements, represented a significant dimension of Skálholt's economic strategy during the early modern period and illuminates the complex relationship between elite ecclesiastical centers and broader patterns of agricultural change in post-medieval Iceland.

6.3 Conclusion: Biometrical Evidence for Agricultural Adaptation at Skálholt

The biometrical analysis of domestic livestock remains from Skálholt provides significant insights into how this elite ecclesiastical center engaged with broader currents of agricultural change during the early modern period. Through multiple analytical approaches – log-ratio scaling, withers height estimation, slenderness indices, and comparative frameworks spanning both time and space – this research has identified distinctive morphological patterns that illuminate specialized management practices at Skálholt and their relationship to broader economic and environmental contexts in post-medieval Iceland.

The examination of cattle morphology revealed several distinctive characteristics that distinguish Skálholt's assemblage. While cattle bones generally demonstrated dimensions comparable to the reference standard (mean log-ratio width = 0.004), specific elements – particularly metacarpals – exhibited significantly larger measurements, suggesting deliberate selection for particular functional traits or

breeding priorities. The consistently wider metacarpal measurements relative to other skeletal elements, including femora and humeri, potentially indicate the presence of bulls or oxen within the assemblage, aligning with documentary evidence for specialized management at high-status farms. When compared with contemporaneous English material from The Shires, Skálholt's cattle show significantly smaller dimensions, indicating a distinctive Icelandic adaptation rather than wholesale adoption of the dramatic size increases associated with England's Second Agricultural Revolution (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013). However, the presence of naturally and artificially polled specimens at Skálholt, documented in previous analyses (Hambrecht 2011, 2012; Utsunomiya et al. 2017), suggests selective engagement with European improvement concepts, adapted to Iceland's specific environmental constraints.

The sheep assemblage demonstrated even more pronounced evidence for specialized management and potential improvement. Skálholt's sheep exhibited significantly increased dimensions compared to earlier Icelandic sites, particularly in length measurements, with withers heights (metacarpal mean = 64.22 cm) substantially exceeding those from Viking Age and medieval assemblages. The differential pattern between length and width measurements – with greater increases in length than width – strongly suggests both selective breeding and specialized wether management for wool production. This interpretation is reinforced by the reduced variability in slenderness indices at Skálholt compared to other sites, indicating standardized management practices consistent with the site's administrative capacity and economic resources. When situated within broader North

Atlantic contexts, Skálholt's sheep occupied an intermediate position between the surprisingly large Greenlandic specimens and the smaller Shetland populations, highlighting regionally specific adaptations shaped by both environmental constraints and institutional priorities.

The combined evidence from both cattle and sheep assemblages suggests that Skálholt represented not simply emulation of European agricultural models but rather a distinctively Icelandic engagement with broader currents of agricultural innovation. Rather than wholesale adoption of new breeds or dramatic size increases, the evidence indicates selective improvement within established livestock populations, focusing on specific traits and management practices aligned with particular economic objectives. This approach – enhancing native stock through selective breeding while maintaining adaptations to Iceland's marginal environment – represents a sophisticated response to both European influences and Icelandic realities during a period of significant agricultural transition (Hambrecht 2015; McGovern et al. 2007).

These findings align with documentary evidence regarding agricultural innovation at Skálholt, including Björn Halldórsson's agricultural manual and barley cultivation (Einarsson 1982; Halldórsson 1948, in Hambrecht 2011). They further demonstrate the significant role of elite ecclesiastical centers in agricultural development, where institutional resources, European connections, and administrative capacities enabled specialized management approaches that differed from practices at ordinary farms. The biometrical evidence thus illuminates not just livestock morphology but broader patterns of socioeconomic organization and ecological

adaptation in early modern Iceland, where environmental constraints, cultural traditions, and European influences combined to shape distinctive agricultural strategies at elite ecclesiastical centers like Skálholt (Lucas and Snæsdóttir 2022; Júlíusson et al. 2020).

The morphological patterns identified through this research demonstrate that while Skálholt participated in the broader currents of agricultural change that transformed European livestock during the "long" sixteenth century, it did so through distinctively Icelandic adaptations calibrated to local environmental constraints and institutional needs. This regionally specific approach to agricultural innovation, balancing traditional adaptations with selective enhancements, represents a significant dimension of Skálholt's economic strategy during the early modern period. More broadly, these findings highlight the complex processes through which agricultural innovations diffused across early modern Europe, as peripheral regions like Iceland selectively adapted continental models to distinctive environmental conditions and socioeconomic structures (Hambrecht 2012; Thomas et al. 2013).

Chapter 7: Discussion

7.1 Skálholt as a Center of Agricultural Adaptation

The biometrical analysis of cattle and sheep remains from Skálholt has established several key findings. First, the cattle remains revealed evidence for specialized management practices that distinguish Skálholt from typical Icelandic sites, including possible evidence for beef-focused production in what was predominantly a dairy-oriented economy. The distinctive pattern of metacarpal dimensions suggests the potential presence of males (either bulls or steers) within the assemblage, reflecting the site's capacity to maintain these resource-intensive animals. Second, the sheep assemblage demonstrated compelling evidence for both specialized wether management and potential selective improvement, with consistently larger dimensions compared to earlier Icelandic sites, particularly in length measurements. The distinctive relationship between length and width dimensions strongly suggests deliberate breeding strategies focused on wool production, a pattern consistent with Skálholt's documented status as a major landowner with extensive sheep holdings.

When situated within broader comparative frameworks spanning the North Atlantic region, these findings reveal complex patterns of regional adaptation and specialized management that challenge simplistic narratives of agricultural improvement. Rather than directly emulating English agricultural models – which during this period focused on dramatic size increases through new breed introductions – Skálholt appears to have engaged selectively with improvement concepts, adapting

them to Iceland's distinctive environmental constraints and economic priorities. This regionally specific approach to agricultural innovation represents a sophisticated response to both European influences and Icelandic realities during the early modern period.

The following discussion synthesizes these findings within their broader historical, environmental, and theoretical contexts. It examines Skálholt's role as a center of agricultural adaptation, explores species-specific management strategies, situates these patterns within broader North Atlantic frameworks, and considers their implications for understanding the diffusion of agricultural innovations in marginal regions. Through this integrative approach, we can evaluate how the biometrical evidence illuminates not just livestock morphology but broader patterns of socioeconomic organization and ecological adaptation in early modern Iceland.

The biometrical patterns documented in this dissertation contribute to multiple domains of archaeological inquiry. For economic questions, they provide insights into specialized production strategies, elite consumption patterns, and the allocation of resources within a major ecclesiastical institution. For environmental considerations, they illuminate how livestock adaptations reflected both ecological constraints and human management decisions in Iceland's challenging landscape. For cultural and historical dimensions, they reveal how Skálholt – as a nexus of religious, political, and economic power – potentially mediated between local traditions and external innovations during a significant transitional period in European agricultural history. By integrating these perspectives, this discussion aims to demonstrate the value of biometrical analysis for addressing complex questions about human-animal

relationships in the past and their entanglement within broader social, economic, and environmental systems.

As one of Iceland's two episcopal seats, Skálholt maintained extensive landholdings and substantial economic resources that enabled specialized management practices beyond the capabilities of ordinary farms (Lucas and Snæsdóttir 2022). This institutional capacity extended across approximately 300 properties mostly within its diocese, but with some properties and privileges located outside of its diocese, creating a centralized economic network that facilitated specialized production strategies. Skálholt's economic influence was particularly significant within wool production networks, as the bishopric collected substantial rents in kind, including woollens, from its tenant farmers (Júlíusson et al. 2020). These economic relationships positioned Skálholt as a central node in the flow of materials, including wool and woollen products, which represented major export commodities during the Danish Trade Monopoly period (1602-1787).

The livestock assemblage from Skálholt demonstrates several key characteristics that distinguish it from both earlier Icelandic sites and contemporaneous ordinary farms. The cattle remains exhibit unusual morphological patterns, particularly in metacarpal dimensions, suggesting specialized management practices potentially oriented toward beef production rather than the dairy-focused economy typical of Iceland during this period (Hambrecht 2011, 2012; Hicks 2016). Similarly, the sheep assemblage shows evidence for both specialized wether management and potential selective breeding, with consistently larger dimensions compared to Viking Age and medieval sites, especially in length measurements.

These distinctive patterns indicate deliberate management strategies rather than simply environmental adaptations.

Environmental factors undoubtedly influenced livestock morphology at Skálholt, as at all Icelandic sites. Iceland's sub-arctic volcanic landscape, with its limited growing season and vulnerability to soil erosion, imposed significant constraints on agricultural practices throughout the island's settlement history (Dugmore et al. 2005; McGovern et al. 2007). By the seventeenth and eighteenth centuries, substantial environmental degradation had occurred across Iceland, with approximately forty percent of rangeland grazing pastures exhibiting severe erosion (Arnalds et al. 2001; Brown et al. 2012). These environmental challenges required adaptive management strategies, particularly for maintaining larger livestock like cattle.

However, the biometrical evidence suggests that Skálholt's livestock management transcended simple environmental adaptation. The statistically significant differences between Skálholt's sheep assemblage and those from both earlier sites and contemporaneous farms indicate deliberate breeding strategies rather than merely differential access to resources. The reduced measurement variability, particularly in slenderness indices, suggests standardized management practices that would have required substantial institutional capacity.

7.2 Species-Specific Management Strategies

The management strategies evident in the faunal assemblage reflect Skálholt's institutional capacity to implement specialized approaches beyond the capabilities of

ordinary farms. As one of Iceland's two episcopal seats, Skálholt controlled substantial resources, including extensive landholdings, specialized labor, and administrative structures that facilitated complex management regimes (Júlíusson et al. 2020; Lucas and Snæsdóttir 2022). This institutional context enabled differentiated species management aligned with specific economic objectives and status considerations, rather than the more generalized subsistence-focused approaches typical of smaller farms (McGovern et al. 2007).

The distinctive patterns observed in each species reveal not only management priorities but also the economic and social significance of different livestock within early modern Icelandic society. These species-specific strategies should be understood within the broader context of post-medieval Iceland's economic transition, where traditional subsistence practices increasingly interfaced with market-oriented production and elite consumption patterns (Hambrecht 2015). The following sections examine the distinctive management approaches for cattle and sheep at Skálholt, considering both their practical agricultural dimensions and their broader socioeconomic significance.

7.2.1 Cattle Management at an Elite Ecclesiastical Center

The biometrical analysis of cattle remains from Skálholt reveals several distinctive characteristics that suggest specialized management practices unusual within the predominantly dairy-focused economy of early modern Iceland (Hicks 2016). While cattle constituted a proportionally smaller component of the overall livestock economy compared to sheep, their material presence at Skálholt –

particularly the evidence for distinctive morphological characteristics – indicates specialized approaches that likely reflected both practical economic considerations and status-related consumption patterns.

The most striking pattern in the cattle assemblage is the disproportionately higher log-ratio values for metacarpal measurements compared to other skeletal elements. While metacarpals exhibited a positive mean log-ratio value (0.0712 ± 0.0224), other limb elements like the femur (-0.0172 ± 0.0290) and humerus (-0.00724 ± 0.0466) showed values closer to or below zero. This statistically significant difference ($p = 0.0131$ between metacarpal and femur; $p = 0.0419$ between metacarpal and humerus) suggests the presence of animals with distinctive morphological characteristics, potentially indicating bulls or steers within the assemblage. The consistently wider metacarpal measurements, combined with relatively low variability, points toward deliberate selection or management strategy rather than random variation.

This pattern is particularly significant given the documented shift in cattle-to-sheep ratios throughout Iceland's post-settlement history. While earlier Viking Age sites maintained cattle-to-sheep ratios approaching 1:4, later medieval and post-medieval sites typically show ratios of 1:10 or higher, reflecting adaptation to Iceland's deforested landscape and challenging winter foddering requirements (McGovern et al. 2007, 2009). Skálholt's higher percentage of cattle remains compared to contemporaneous ordinary farms represents a departure from this general trend, suggesting that this elite institution maintained larger cattle herds than

were typical for the period, despite the greater resource demands these animals represented (Hambrecht 2011).

The presence of both naturally and artificially polled cattle, identified in previous analyses of the Skálholt assemblage (Hambrecht 2011, 2012), provides further evidence for specialized breeding practices. Genetic research has confirmed that the POLLED mutation has been present in Icelandic cattle for at least 1,000 years (Utsunomiya et al. 2017), indicating that the polled specimens at Skálholt represent selective breeding for this trait rather than wholesale introduction of new stock. This selective breeding for polledness – a trait that facilitates easier management by eliminating dangerous horns – suggests sophisticated husbandry practices aligned with continental European agricultural innovations, yet implemented within Iceland's established cattle population.

Withers height reconstructions from Skálholt cattle provide additional context for understanding management practices at this elite center. The Skálholt specimens (mean metatarsal-derived height = 105.70 cm) show dimensions slightly below those of earlier Icelandic sites like Sveigakot (108.92 cm), Hrísheimar (109.79 cm), and Gásir (110.64 cm). This pattern contrasts sharply with contemporaneous English material from The Shires (mean metacarpal-derived height = 115.79 cm), where the "long" sixteenth century saw substantial size increases associated with agricultural improvement movements (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013). Rather than emulating these dramatic size increases, Skálholt appears to have maintained traditionally-sized Icelandic cattle while selectively breeding for specific traits like polledness.

This management approach likely reflects adaptation to Iceland's environmental constraints. Despite Skálholt's elite status and substantial resources, the challenging sub-arctic environment – with its short growing season, vulnerability to winter starvation, and limited fodder production – would have imposed significant constraints on cattle management. The maintenance of medium-sized polled cattle rather than larger imported breeds would have represented a pragmatic compromise between status considerations and environmental realities, allowing Skálholt to maintain distinctive cattle without excessive resource requirements.

The economic significance of cattle at Skálholt extended beyond simple subsistence. Júlíusson (1997) notes that historical sources indicate that cattle, particularly steers, represented valuable commodities for both traction and meat production in medieval and post-medieval Iceland. The potential presence of male cattle at Skálholt, suggested by the metacarpal measurements, might indicate specialized economic roles beyond dairying. Additionally, beef consumption represented a significant status marker in Icelandic society (Hambrecht 2011). Skálholt's capacity to maintain cattle for meat production rather than solely for dairy would have reinforced its elite status within Iceland's social hierarchy.

When positioned within broader North Atlantic contexts, Skálholt's cattle management shows distinctive characteristics that reflect both local adaptation and selective engagement with European agricultural trends. Unlike roughly-contemporaneous English sites, where dramatic size increases reflected wholesale adoption of new breeds and intensive management practices, Skálholt maintained traditionally-sized Icelandic cattle while selectively breeding for specific traits. This

approach more closely resembles the conservative management documented in other North Atlantic regions like the Western Settlement in Greenland, where environmental constraints similarly encouraged maintenance of traditional stock (Cussans 2017; Grau-Sologestoa and Albarella 2019; McGovern 1985).

The archaeological context of Skálholt's cattle remains provides additional insights into consumption patterns at this elite center. The concentration of cattle bones in Midden Zone C, particularly context [454], suggests specialized butchery activities potentially associated with the documented meat storage facility nearby (Hambrecht 2011; Lucas and Snæsdóttir 2022). This spatial pattern aligns with historical evidence for specialized functional zones within the Skálholt complex, including areas dedicated to food processing and storage. The potential for male cattle elements in these contexts suggests potential specialized butchery practices focused on beef production rather than the dairy-oriented management typical of ordinary Icelandic farms.

Cattle management at Skálholt demonstrates a sophisticated approach that balanced elite status considerations with environmental constraints. The morphological evidence suggests selective breeding for specific traits like polledness rather than wholesale adoption of European improvement models focused on size maximization. This selective approach, combined with the maintenance of larger cattle herds than were typical for contemporaneous ordinary farms, reinforced Skálholt's distinctive economic position within early modern Iceland while demonstrating pragmatic adaptation to environmental limitations. The cattle assemblage thus provides compelling evidence for how elite ecclesiastical centers

navigated both local environmental realities and broader European agricultural currents during this transitional period.

7.2.2 Sheep Husbandry and Wool Production

The biometrical analysis of sheep remains from Skálholt reveals compelling evidence for specialized management practices focused on wool production through wether maintenance. Unlike cattle, which represented a proportionally smaller component of Iceland's pastoral economy, sheep constituted the foundation of agricultural production throughout the medieval and post-medieval periods, providing wool, meat, and milk for both subsistence and exchange (McGovern et al. 2007). The distinctive morphological patterns observed in the Skálholt assemblage suggest that this elite ecclesiastical center implemented sophisticated sheep management strategies that reflected both its institutional capacity and specific economic priorities.

The most significant pattern in the sheep assemblage is the distinctive relationship between length and width measurements. Skálholt sheep demonstrate significantly greater positive deviation from the reference standard in length measurements (mean = 0.033) than in width measurements (mean = 0.019), with this difference being statistically significant ($p = 0.00502$). This pattern – more pronounced increases in length than width – represents a distinctive morphological signature that aligns with documented effects of castration, where delayed epiphyseal fusion allows continued longitudinal growth without corresponding increases in bone width (Davis 2000; Popkin et al. 2012). The combination of significantly increased

metacarpal length with relatively moderate width increases provides strong evidence for a substantial wether component within the Skálholt flock.

This interpretation is further supported by the metapodial morphology analysis. The scatterplots of greatest length (GL) versus distal breadth (Bd) for metacarpals illustrate a distribution pattern consistent with a mixed population including both ewes and wethers. Following Davis (2000) and Popkin and colleagues (2012), wethers would be expected to cluster in the upper left quadrant of such plots, with longer but relatively narrow bones compared to both ewes (lower left) and rams (upper right). The presence of several specimens in precisely this position on the metacarpal plot strongly suggests the maintenance of castrated males within the Skálholt flock.

Withers height reconstructions provide additional evidence for specialized sheep management at Skálholt. The estimated heights based on metacarpal measurements (mean = 64.22 cm) significantly exceed those from earlier Icelandic sites including Hofstaðir (61.47 cm), Hrísheimar (60.04 cm), and Sveigakot (60.27 cm). These substantial differences – 2.75 cm taller than Hofstaðir, 4.18 cm taller than Hrísheimar, and 3.95 cm taller than Sveigakot – represent statistically significant variations that exceed normal population variability. This increased stature, most pronounced in metacarpal-derived estimates, aligns with the expected effects of specialized wether management, as castrated males typically develop taller stature than ewes.

The slenderness indices provide particularly valuable insights into sheep management practices at Skálholt. While the metacarpal slenderness means show

minimal variation across sites (Skálholt = 10.6; Hofstaðir = 10.7; Hrísheimar = 10.8), Skálholt exhibits substantially reduced variability (SD = 0.636) compared to earlier sites. This reduced variation suggests standardized management practices that would have required substantial institutional capacity to implement consistently across flocks. The standardization aligns with Skálholt's documented administrative capabilities and economic resources, which would have facilitated more controlled breeding and management regimes than were possible at smaller farms (Júlíusson et al. 2020).

The comparative analysis across the North Atlantic provides additional context for understanding Skálholt's sheep management strategies. The intermediate position of Skálholt's sheep measurements between the larger Greenlandic specimens and smaller Shetland populations suggests a distinctive regional adaptation shaped by both environmental constraints and institutional priorities. This pattern contrasts with the island dwarfism evident in the Old Scatness assemblage from Shetland, where genetic isolation and environmental adaptation produced consistently smaller dimensions aligned closely with the Soay reference standard (Dockrill et al. 2013). Skálholt's contrasting pattern of increased dimensions suggests deliberate enhancement rather than simple environmental adaptation.

The evidence for specialized wether management aligns with documentary evidence regarding wool production at ecclesiastical estates during this period. Historical sources indicate that wethers were specifically maintained for wool production, with their more consistent fleece quality and higher wool yields compared to breeding ewes (Ingimundarson 1995). Wool represented a fundamental economic

resource in early modern Iceland, functioning not merely as a subsistence necessity but as a cornerstone of the island's economic system (Róbertsdóttir 2008). From the medieval period through the eighteenth century, woven wool cloth (*vaðmál*) served as a primary currency for both domestic and international transactions, facilitating tax payment, rent collection, and mercantile exchange. During the Danish Trade Monopoly period (1602-1787), woollen products constituted Iceland's second most valuable export commodity after fish and meat products, with Danish authorities implementing systematic initiatives to enhance sheep farming efficiency, improve wool yields, and standardize production quality (Róbertsdóttir 2014). The institutional context of Skálholt, with its extensive landholdings and administrative capacity, would have facilitated specialized production strategies focused on maximizing wool quality and quantity rather than simply ensuring subsistence-level productivity.

As one of Iceland's largest landowners, controlling approximately 300 properties throughout its diocese, Skálholt functioned as a central node in regional economic networks, collecting substantial rents and tithes in kind – including woollens – from its numerous tenant farmers (Júlíusson et al. 2020). The bishopric's position within these material flows would have incentivized strategic management of sheep resources to optimize wool production quality and consistency, particularly as Danish authorities intensified efforts to standardize production during the eighteenth century.

The dimensional increase in Skálholt sheep compared to earlier Icelandic assemblages raises questions about potential breed improvement or introduction.

However, several lines of evidence suggest this more likely represents enhancement through selective breeding and improved management practices than wholesale breed replacement:

First, the dimensional increase appears more substantial in length measurements than in width measurements, a pattern consistent with wether-focused husbandry rather than fundamental breed changes. Second, the reduced variability in slenderness indices suggests standardized management rather than mixed breed introduction, which would typically increase measurement variability. Third, the historical context of the seventeenth and eighteenth centuries aligns with documented agricultural improvement efforts at Skálholt, including barley cultivation (Hambrecht 2011, 2012).

The chronological positioning of Skálholt's assemblage during the seventeenth and eighteenth centuries places it within the broader context of European agricultural transitions. While English agricultural improvement during this period often focused on dramatic size increases through new breed introductions, Skálholt's approach appears more calibrated to Iceland's specific environmental constraints and economic priorities (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013). Rather than wholesale adoption of English improvement models focused on meat production, Skálholt's sheep management suggests selective adaptation of improvement concepts within a wool-focused economic strategy.

The bimodality analysis further illuminates the demographic composition of Skálholt's sheep population. While Hartigans' dip test ($p = 0.232$) indicates no statistically significant bimodality in the metacarpal withers height distribution,

mixture analysis suggests the potential presence of two components: a primary group comprising approximately 69% of animals with a mean height of 62.45 cm, and a secondary group comprising about 31% of animals with a mean height of 68.2 cm. This pattern likely reflects the demographic composition of ewes and wethers rather than distinct breeds, aligning with specialized wool production strategies where wethers would be maintained alongside breeding ewes.

The reduction in measurement variability at Skálholt compared to earlier sites has important implications for understanding management intensity. While Viking Age and medieval assemblages show considerable variability in sheep measurements, suggesting diverse management strategies during early adaptation to Iceland's environment, Skálholt's more consistent patterns indicate deliberate selection and specialized management. This standardization suggests that Skálholt leveraged its institutional resources to implement more controlled breeding and management regimes than were feasible at ordinary farms, potentially including selective culling of less desirable animals, carefully planned breeding strategies, and specialized feeding regimes.

The biometrical evidence from Skálholt's sheep assemblage provides compelling evidence for specialized management practices focused on wool production through wether maintenance. The distinctive morphological patterns – including increased length relative to width dimensions, taller withers heights, reduced measurement variability, and distribution patterns consistent with castrate presence – collectively indicate sophisticated husbandry strategies aligned with the site's institutional capacity and economic priorities. These findings situate Skálholt

within the broader context of early modern agricultural developments while highlighting distinctively Icelandic adaptations to environmental constraints and economic objectives.

7.3 North Atlantic Perspectives on Livestock Adaptation

The comparative analysis of livestock morphology across the North Atlantic region provides valuable insights into how environmental conditions, cultural practices, and institutional contexts shaped animal management strategies in different insular settings. By examining biometrical patterns from Iceland, Greenland, and Shetland, we can identify distinctive regional adaptations that reflect complex interactions between environmental constraints, cultural traditions, and economic priorities. This broader geographical perspective enhances our understanding of Skálholt's livestock management strategies by situating them within regional patterns of adaptation and divergence.

The most striking pattern to emerge from this comparative analysis is the unexpected dimensional relationship between Greenlandic, Icelandic, and Shetland sheep. Contrary to straightforward environmental determinism, which would predict the smallest sheep in Greenland's challenging environment and the largest in more temperate Shetland, the biometrical evidence reveals a different pattern. Greenlandic sheep exhibit significantly larger dimensions (length mean = 0.0303) than Old Scatness specimens (mean = 0.0001), with Icelandic sites, including Skálholt, occupying an intermediate position (mean = 0.0191). This pattern is particularly

pronounced in length measurements, which typically show greater resistance to nutritional stress than width dimensions (Pálsson and Vergés 1952a, b).

This unexpected dimensional ordering challenges simplistic correlations between environmental marginality and livestock size. The Norse settlements in Greenland represent the most environmentally challenging of these North Atlantic colonies, with shorter growing seasons, more limited grazing resources, and eventually fatal environmental constraints (Dugmore et al. 2012; McGovern 2000). Yet the sheep remains from these settlements demonstrate consistently larger dimensions than those from more temperate regions, contradicting straightforward applications of biogeographical principles like Bergmann's rule, which associates larger body size with colder environments, or Geist's modification, which links body size with nutritional availability during growing seasons (Davis 19821; Geist 1987).

Several interpretations might explain Greenland's unexpectedly large sheep. First, they could reflect deliberate selection of larger, hardier animals during the initial settlement, potentially representing a "founder effect" where colonists preferentially transported robust livestock to this challenging new environment (McGovern et al. 2014). This selective process would align with documentary evidence suggesting that Greenlandic settlement was more carefully planned than the earlier Icelandic colonization, with deliberate resource selection for the new colony (Arneborg et al. 2012). Second, the larger dimensions might reflect adaptive responses to Greenland's distinctive environmental conditions, particularly its extreme seasonality with extended darkness in winter and continuous daylight in summer, creating distinctive growth patterns, though this would perhaps be less

impactful with such relatively minor differences in latitude (McGovern 1985). Third, they could indicate more intensive management necessitated by environmental constraints, with archaeological evidence suggesting smaller overall herd sizes but more intensive care, including extended indoor stabling during the prolonged winter period (Dugmore et al. 2012; McGovern 2000).

In contrast, the consistently smaller dimensions of sheep from Old Scatness in Shetland (length mean = 0.0001; width mean = 0.0116) align with expectations for long-established insular populations. The dimensional patterns at this site, with mean values close to zero (indicating minimal deviation from the Soay reference standard), suggest minimal morphological change from primitive northern short-tailed sheep morphotypes like the Soay (Clutton-Brock et al. 1990; Ryder 1983). This pattern is consistent with the biogeographical principle of island dwarfism, where genetically isolated populations on islands frequently exhibit size reduction compared to mainland counterparts (Marshall and Corruccini 1978). The Old Scatness assemblage spans the post-medieval to crofting periods (seventeenth-nineteenth centuries AD), representing a long-established sheep population adapted to Shetland's distinctive environmental conditions (Dockrill et al. 2013).

The intermediate position of Icelandic sheep, including those from Skálholt, suggests a distinctive adaptive pathway shaped by multiple factors. Iceland's environmental conditions fall between Greenland's extreme challenges and Shetland's more temperate climate, but environmental parameters alone cannot explain the observed morphological patterns. The significant variation between Icelandic sites – with notably larger sheep at specialized economic centers like Gásir

(length mean = 0.067) compared to sites like Hofstaðir (length mean = 0.018) – indicates that cultural and economic factors substantially influenced livestock morphology alongside environmental constraints. Skálholt's position within this Icelandic spectrum (length mean = 0.033) reflects its distinctive institutional context, where elite status and substantial resources enabled specialized management practices that produced morphologically distinctive livestock.

When examining these regional patterns through the lens of island biogeography, several important principles emerge. While island dwarfism appears evident in the Shetland assemblage, Greenlandic and Icelandic populations demonstrate more complex adaptive patterns that contradict simple dwarfism models. This complexity likely reflects the interaction between genetic factors (including potential founder effects during initial colonization), environmental constraints (particularly growing season duration and quality), and cultural practices (especially management intensity and selective breeding). The differential expression of these factors across the North Atlantic created distinctive regional morphologies that cannot be reduced to simple environmental determinism.

The relationship between length and width measurements provides additional insights into regional adaptation patterns. Across all three regions, length measurements show greater differentiation than width measurements, with Old Scatness demonstrating a smaller difference between length and width values than either Icelandic or Greenlandic assemblages. This differential relationship between dimensions suggests region-specific responses to environmental constraints, with potential implications for understanding adaptation mechanisms. The reduced width-

to-length ratios in both Greenlandic and Icelandic sheep might reflect adaptations to resource limitations, where reduced robusticity could represent an energy-conservation strategy while maintaining overall frame size (Pálsson and Vergés 1952a).

Environmental constraints in marginal North Atlantic environments may create inherent limits on viable size ranges, regardless of average dimensions. As Ross and colleagues (2016) note, sheep grazing across the North Atlantic region has shaped landscapes and biodiversity while adapting to distinct environmental challenges. These constraints could produce similar absolute variation ranges despite different mean values as sheep populations respond to the boundaries of viability in these marginal environments.

The similarity in absolute variation across regions with significantly different mean values has important implications for understanding livestock management strategies. Rather than indicating random variation, these patterns suggest that sheep populations across the North Atlantic were managed through approaches that maintained consistent phenotypic ranges while focusing on different target morphologies that suited local environmental conditions and economic priorities.

Chronological considerations further complicate these regional comparisons. The Greenlandic material primarily dates to the fourteenth and fifteenth centuries, representing the terminal phase of Norse settlement before abandonment around 1450 AD (McGovern 1985). The Icelandic assemblages span a broader temporal range, from Viking Age sites like Hofstaðir (tenth-eleventh centuries) to early modern contexts like Skálholt (seventeenth-eighteenth centuries). The Old Scatness material

derives from post-medieval and crofting contexts (seventeenth-nineteenth centuries), roughly contemporaneous with Skálholt but representing a very different economic and cultural context (Dockrill et al. 2013). These chronological differences introduce additional variables when interpreting morphological patterns, as environmental conditions, management practices, and genetic stocks all changed over time.

Skálholt's position within these broader North Atlantic patterns offers valuable insights into its distinctive adaptive strategy. Unlike the Shetland pattern of island dwarfism and primitive morphology, Skálholt demonstrates evidence for selective enhancement through specialized management. Unlike the Greenlandic pattern of unexpectedly large dimensions potentially reflecting founder effects or extreme management intensity, Skálholt shows evidence for more moderate dimensional enhancement combined with reduced variability, suggesting standardized management practices aligned with specific institutional priorities. This distinctive position reflects Skálholt's role as an elite ecclesiastical center negotiating between environmental constraints, cultural traditions, and economic objectives during a period of agricultural transition.

These regional patterns illuminate how livestock morphology in the North Atlantic reflected not simple environmental determination but complex adaptive strategies shaped by cultural priorities, environmental limitations, and economic objectives. While all three regions maintained sheep populations adapted to insular environments, each developed distinctive morphological characteristics aligned with particular adaptive strategies: Greenland's emphasis on intensive management of relatively large, potentially founder-selected animals; Shetland's maintenance of

smaller, hardy primitive types focused on wool quality; and Iceland's diverse approaches ranging from specialized production at sites like Gásir and Skálholt to subsistence strategies at ordinary farms. These regional variations demonstrate the complex interplay between environmental constraints and cultural practices in shaping livestock adaptation across the North Atlantic.

7.4 Livestock Improvement in Early Modern Iceland

The comparison between Skálholt's livestock assemblage and contemporary English material provides particularly valuable perspectives on differing improvement trajectories. The '"long" sixteenth century' (c. 1450-1650) in England witnessed substantial livestock transformations, including significant size increases in both cattle and sheep (Grau-Sologestoa and Albarella 2019; Thomas et al. 2013). This period saw English livestock dimensions increase dramatically, with both genetic changes through new breed introductions and enhanced management practices contributing to these transformations. The cattle from The Shires in Leicester exemplify these changes, with metacarpal-derived withers heights averaging 115.79 cm – substantially exceeding contemporaneous Icelandic means, including those from Skálholt (105.70 cm). This dimensional disparity, confirmed through statistical analysis ($p < 0.001$, Cohen's $\delta = -0.841$), indicates fundamentally different trajectories in livestock development between these regions despite their contemporaneity.

However, the absence of dramatic size increases in Iceland does not indicate a lack of engagement with agricultural improvement concepts. Rather, the evidence

from Skálholt suggests a more nuanced approach focused on selective enhancement of specific traits rather than wholesale size increase. For cattle, this selective approach is exemplified by the presence of both naturally and artificially polled specimens, which paleogenetic data has confirmed reflect selective breeding for the POLLED mutation that has been present in Icelandic cattle for at least 1,000 years (Hambrecht 2011, 2012; Utsunomiya et al. 2017). This selective breeding for polledness suggests sophisticated husbandry practices aligned with continental European agricultural innovations, yet implemented within Iceland's established cattle population.

For sheep, the selective enhancement appears focused on wool production through specialized wether management. The distinctive pattern of greater increases in length than width measurements, combined with reduced variability in slenderness indices, suggests standardized management practices aimed at enhancing specific productive characteristics rather than simple size maximization. This approach differs from the English emphasis on meat production that typically produced more robust, shorter-limbed animals during this period (Thomas 2005). The intermediate position of Skálholt's sheep between earlier Icelandic assemblages and continental European improved breeds suggests deliberate enhancement of established Icelandic populations rather than their wholesale replacement with imported stock.

Environmental constraints significantly influenced these improvement trajectories in Iceland. Despite Skálholt's elite status and substantial resources, the challenging sub-arctic environment – with its short growing season, limited hay-producing capacity, and vulnerability to climate fluctuations – would have imposed significant limitations on potential innovations (Dugmore et al. 2005; McGovern et

al. 2007). The maintenance of medium-sized polled cattle and specialized wether flocks, rather than introducing larger continental breeds with increased resource requirements, represented a pragmatic adaptation to these environmental realities. This pattern exemplifies what might be termed "calibrated improvement" – enhancing specific livestock characteristics aligned with institutional priorities while maintaining adaptations to local environmental constraints.

Documentary evidence further illuminates these improvement efforts at Skálholt. The agricultural manual *Atli* by Björn Halldórsson, composed in the late eighteenth century, explicitly engaged with contemporary European agricultural improvement discourse (Halldórsson 1948, in Hambrecht 2011). While this text postdates much of the Skálholt assemblage, it reflects an intellectual environment where agricultural improvement was valued and pursued. More direct evidence comes from palynological analysis documenting a significant spike in barley pollen in seventeenth-century soil samples from Skálholt, suggesting some early work with cultivation efforts at this ecclesiastical center (Einarsson 1982). These documented innovation attempts align with the biometrical evidence for specialized livestock management, reinforcing Skálholt's characterization as a locus of agricultural experimentation within early modern Iceland.

The selective nature of improvement at Skálholt contrasts with contemporaneous approaches elsewhere in Europe, particularly England's more wholesale transformations. While English improvement during this period increasingly emphasized standardized breeding, scientific management, and the importation of new livestock varieties, Skálholt's approach appears more incremental

and selective. This difference likely reflects both practical limitations imposed by Iceland's insular geography and deliberate choices regarding which innovations would prove most beneficial within the Icelandic context. Rather than uncritically adopting external models, the evidence suggests Skálholt's administrators strategically selected specific improvement concepts that aligned with institutional priorities while remaining feasible within environmental constraints.

Elite institutions like Skálholt played a crucial role in mediating continental European innovations within Iceland. As a center of literacy, international connection, and substantial economic resources, the ecclesiastical estate possessed both the knowledge networks to access external innovations and the capacity to implement them (Júlíusson et al. 2020; Lucas and Snæsdóttir 2022). Skálholt's extensive landholdings enabled experimentation across diverse environmental settings, while its administrative structures facilitated coordinated management implementation across multiple farms. These institutional capacities distinguished this ecclesiastical center from ordinary farms, enabling specialized agricultural strategies beyond the capabilities of individual farmers operating with more limited resources and knowledge networks.

The chronological context further illuminates Skálholt's improvement trajectory. The seventeenth and eighteenth centuries represented a transitional period in European agricultural history, with the "Second Agricultural Revolution" transforming farming practices across multiple regions (Kerridge 1967; Overton 1996). However, others have emphasized the gradual and uneven nature of these transformations, with significant regional variations in both timing and

implementation (Allen 1999; Thomas 2005). Skálholt's selective engagement with improvement concepts exemplifies this complex pattern, demonstrating how peripheral regions adapted broader agricultural movements to their specific contexts rather than following uniform trajectories of change.

The socioeconomic dimensions of livestock improvement at Skálholt warrant particular consideration. As one of Iceland's two episcopal seats, Skálholt maintained substantial wealth, extensive landholdings, and significant social power throughout the medieval and early modern periods (Hambrecht, 2011; Lucas and Snæsdóttir, 2022). This elite status facilitated specialized livestock management in several ways: providing financial resources for innovative experiments; creating administrative structures for implementing coordinated strategies across multiple farms; allowing risk absorption from unsuccessful innovations; and establishing networks for accessing external knowledge. The interplay between elite status and improvement thus operated bidirectionally – elite status enabled specialized management, while innovative practices reinforced institutional distinction and status (Júlíusson et al. 2020).

In broader historical context, Skálholt's approach to livestock improvement exemplifies what historians have termed the "Icelandic Enlightenment" or "Iceland's Great Revival" during the eighteenth century (Karlsson 2000; Parigoris 2022). This intellectual movement, while influenced by European Enlightenment currents, developed distinctive characteristics adapted to Iceland's specific environmental and cultural contexts. Rather than simple imitation of external models, this period saw critical engagement with European concepts while maintaining continuity with

Icelandic traditions and adaptations. The selective improvement practices documented at Skálholt embody this broader pattern of adaptive innovation, where external influences were filtered through local knowledge systems and environmental realities.

These processes of selective enhancement and adaptation, rather than wholesale adoption of external models, characterize agricultural improvement in early modern Iceland more broadly. While Iceland's geographical isolation and environmental challenges limited certain innovation possibilities, they did not preclude engagement with broader European agricultural currents. Instead, they shaped distinctive trajectories of improvement calibrated to local conditions and priorities. Skálholt, with its institutional resources and elite connections, represents a particularly clear example of this selective engagement – implementing specific improvements while maintaining adaptations to Iceland's marginal environment.

The biometrical evidence from Skálholt thus contributes to more nuanced understanding of agricultural improvement in peripheral regions during early modern Europe. Rather than depicting improvement as a binary process – either wholesale adoption or complete rejection of continental innovations – the Skálholt assemblage demonstrates a more sophisticated trajectory combining selective implementation of specific concepts with continued adaptation to local environmental constraints. This pattern challenges both diffusionist perspectives that privilege core regions as innovation sources and isolationist frameworks that emphasize peripheral autonomy, suggesting instead complex networks of knowledge exchange and adaptation across geographical and cultural boundaries (Chakrabarty 2000; Tsing 2005).

7.5 Methodological Assessment and Theoretical Implications

The application of integrated biometrical analysis to the Skálholt assemblage has demonstrated both strengths and limitations of this approach for investigating livestock management in post-medieval Iceland. By applying multiple analytical techniques to a well-preserved zooarchaeological collection, this research has revealed distinctive patterns that illuminate how an elite ecclesiastical center engaged with continental European agricultural innovations while adapting to local environmental constraints. This methodological assessment examines the strengths and limitations of the analytical approaches employed, while the theoretical discussion explores how the findings contribute to broader conceptual frameworks for understanding agricultural adaptation in marginal environments.

7.5.1 Methodological Contributions and Limitations

The integrated biometrical approach applied to the Skálholt assemblage has demonstrated both methodological strengths and limitations for investigating livestock management in post-medieval Iceland. The log-ratio scaling technique proved especially valuable for addressing sample size challenges inherent in North Atlantic zooarchaeological assemblages. By converting measurements to dimensionless values relative to standard reference specimens, this method facilitated the pooling of different skeletal elements to increase analytical robusticity while maintaining statistical rigor (Meadow 1999; Simpson 1941; Wolfhagen 2020). This technique substantially enhanced the statistical power of analyses, particularly for the

Skálholt cattle assemblage, where only specific elements like metacarpals provided sufficient individual samples for traditional univariate analysis.

The separate analysis of length and width dimensions revealed patterns that would have remained obscured through aggregated approaches. This analytical distinction confirmed that different measurement types respond differently to various morphological influencing factors, including sexual dimorphism, castration effects, nutritional status, and breed characteristics (Grau-Sologestoa et al. 2021; Zeder and Lemoine 2020). In sheep, length measurements demonstrated greater positive deviation from reference standards than width measurements, suggesting specialized wether management focused on wool production – a pattern consistent with Skálholt's documented status as a major landowner with extensive sheep holdings.

Despite these methodological strengths, several limitations warrant acknowledgment. The uneven distribution of measurements across different elements and dimensions represents an inherent challenge, with length measurements consistently less abundant than width measurements due to preservation patterns where complete long bones survive less frequently than epiphyseal ends. This imbalance potentially influenced interpretations, particularly for cattle where limited length measurements precluded systematic analysis of length-to-width relationships that proved so valuable for sheep.

Additionally, chronological disparities between comparative assemblages introduced interpretive challenges. While the Skálholt material derives primarily from the seventeenth and eighteenth centuries, comparative Icelandic assemblages span from the early settlement period through the medieval period. These temporal

differences introduce potential confounding variables, as environmental conditions, management practices, and genetic stocks shifted over time. Despite these limitations, the multi-scalar comparative framework – examining patterns within Skálholt, across different Icelandic sites, and between broader North Atlantic regions – provided crucial contextual perspectives that strengthened interpretations.

Perhaps the most significant methodological challenge remains the inherent limitations of biometrical analysis for distinguishing between different causal factors affecting morphology. While this research employed multiple approaches to address this complexity, the ultimate attribution of morphological patterns to specific causal factors necessarily involves interpretive judgments based on the convergence of multiple lines of evidence (Albarella 2002). The distinctive relationship between length and width dimensions in Skálholt sheep, for instance, strongly suggests wether management, but this interpretation gains its strongest support when considered alongside historical evidence for wool production priorities at ecclesiastical estates.

7.5.2 Theoretical Implications

The biometrical patterns documented at Skálholt contribute substantively to theoretical discussions regarding agricultural adaptation, technology diffusion, and human-environment interactions in marginal landscapes. By revealing distinctive livestock management strategies at this elite ecclesiastical center, this work challenges simplistic models of agricultural improvement and offers nuanced perspectives on how peripheral regions engaged with broader continental innovations during the early modern period.

One of the most significant theoretical contributions concerns our understanding of agricultural innovation diffusion in peripheral regions. Traditional models of the "Second Agricultural Revolution" often conceptualize innovation as a unidirectional process flowing from core regions to peripheral or marginal areas (Overton 1996; Thomas 2005). The evidence from Skálholt challenges this simplistic diffusion model by demonstrating selective and adaptive engagement with European agricultural concepts rather than wholesale adoption or rejection. The distinctive livestock management strategies evident at Skálholt – combining selective breeding for specific traits like polledness in cattle with traditional dimensional patterns, or enhancing sheep through wether-focused management rather than breed replacement – reveal a more complex process of innovative adaptation that transcends binary adoption/rejection frameworks.

The patterns observed at Skálholt challenge deterministic models that predict straightforward correlations between environmental marginality and agricultural practices. While biogeographical principles like Allen's rule, Bergmann's rule, and Geist's modification provide valuable frameworks for understanding environmental influences on animal morphology, the complex patterns observed across the North Atlantic demonstrate that cultural factors substantially mediated these environmental relationships (Allen 1877, in Millien et al. 2006; Bergmann 1848, in Millien et al. 2006; Cussans 2010; Geist 1987).

The role of elite institutions in agricultural adaptation represents another significant theoretical dimension illuminated by this research. As an ecclesiastical center with extensive landholdings, substantial resources, and connections to

European networks, Skálholt occupied a distinctive institutional position that enabled specialized agricultural strategies beyond the capabilities of ordinary farms (Júlíusson et al. 2020; Lucas and Snæsdóttir 2022). The biometrical evidence suggesting standardized management practices and selective breeding reinforces theoretical perspectives regarding the importance of institutional structures in facilitating innovation in marginal environments, where individual farmers might lack sufficient resources or risk tolerance to experiment with new approaches.

The evidence for both continuity and change in livestock management at Skálholt has implications for theoretical understandings of tradition and innovation in agricultural practices. Rather than representing either rigid adherence to traditional practices or wholesale adoption of external innovations, Skálholt demonstrates a sophisticated integration of both elements – maintaining traditional Icelandic livestock dimensions while selectively incorporating innovative practices like polledness breeding or standardized wether management. The selective enhancement of established Icelandic livestock populations at Skálholt, rather than wholesale replacement with imported breeds, represents neither simple conservation of tradition nor uncritical adoption of innovation, but rather a sophisticated adaptive strategy integrating elements of both.

These theoretical implications collectively suggest the need for more nuanced frameworks that recognize the complex agency through which human societies navigate environmental constraints, cultural traditions, and external influences when developing agricultural strategies in marginal environments (Armstrong et al. 2017). Rather than deterministic models privileging either environmental constraints or

cultural diffusion, the evidence from Skálholt supports theoretical approaches that accommodate multiple causal factors, diverse adaptive pathways, and sophisticated decision-making processes in shaping agricultural practices (Allen et al. 2014; Downey et al. 2016; Gunderson and Holling 2002).

7.6 Broader Significance and Future Directions

The findings from this research have significance that extends beyond the specific case of Skálholt to address broader questions about agricultural adaptation, institutional management, and human-environment interactions in marginal environments. By examining how one of Iceland's most powerful institutions navigated the complex interplay between environmental constraints, cultural traditions, and external influences, this research provides insights that may be relevant to both historical understanding and contemporary challenges.

For historical archaeologists and environmental historians, this study demonstrates the value of integrating biometrical analysis with broader contextual frameworks to develop more nuanced understandings of past agricultural practices. The methodological approach employed here, combining standardized measurement protocols with sophisticated statistical analysis and robust comparative frameworks, provides a model for future research examining livestock management in other historical contexts. By situating biometrical evidence within its historical, environmental, and institutional context, this dissertation illustrates how animal morphology can serve as a window into complex human-environment relationships that might not be visible through other lines of evidence.

For researchers interested in agricultural innovation and technology diffusion, this study offers a case study in how peripheral regions engage with broader currents of agricultural change. The selective adaptation of improvement concepts at Skálholt, calibrated to local environmental conditions and economic priorities, challenges simplistic diffusion models and highlights the agency of local institutions in shaping innovation trajectories. This finding has relevance for understanding how agricultural innovations spread across diverse environmental and cultural contexts, suggesting that successful diffusion often involves substantial local adaptation rather than wholesale adoption of external models.

For scholars studying resilience and adaptation in social-ecological systems, the Skálholt evidence provides insights into how elite institutions maintain specialized practices in challenging environments. The capacity of Skálholt to implement distinctive livestock management strategies – maintaining larger cattle herds and more standardized sheep flocks than typical Icelandic farms – demonstrates how institutional resources can facilitate specialized adaptation to marginal environments. This relationship between institutional capacity and adaptive strategy may have relevance for understanding how different types of social organizations respond to environmental challenges in both historical and contemporary contexts.

For those concerned with contemporary sustainability challenges, this research offers historical perspectives on the complex relationship between elite management, resource allocation, and agricultural adaptation. While direct application of historical lessons requires careful consideration of contextual differences, the long-term view provided by historical ecology can help identify both

successful adaptations and problematic patterns. The Skálholt evidence suggests that effective agricultural adaptation in marginal environments often involves calibrated improvement – enhancing specific aspects of traditional systems while maintaining core adaptations to local conditions – rather than wholesale transformation according to external models.

Several promising directions for future research emerge from this study:

First, expanded analysis of early modern faunal assemblages from diverse site types across Iceland would provide valuable comparative context for the patterns observed at Skálholt. By examining material from ordinary farms, trading centers, and other unique institutional establishments during this period, future research could develop a more comprehensive understanding of how different institutions and communities navigated the agricultural challenges of early modern Iceland.

Second, integration of biometrical analysis with ancient DNA studies offers particularly exciting potential for future research. Genetic analysis could provide direct evidence for breed relationships, selection practices, and population histories that would complement the morphological patterns documented through biometry. Recent advances in palaeogenetics have made such analysis increasingly feasible for archaeological material, offering new possibilities for investigating the biological dimensions of agricultural adaptation (Frantz et al. 2020; Nieto-Espinet et al. 2021).

Third, expanded application of isotopic analysis to faunal remains could provide valuable insights into feeding strategies, mobility patterns, and management practices that would complement biometrical evidence. By analyzing stable isotope signatures in animal bones and teeth, researchers could potentially identify

differences in foddering regimes, grazing locations, and seasonal management that might inform interpretations of morphological patterns. This multi-proxy approach would strengthen understanding of the relationship between management practices and skeletal morphology.

Fourth, more detailed integration of documentary evidence with zooarchaeological material could further illuminate the relationship between institutional policies, economic priorities, and livestock management practices. While this study has drawn on historical sources to contextualize the biometrical patterns observed at Skálholt, more systematic analysis of estate records, trade documentation, and agricultural treatises could provide additional insights into how elite institutions like Skálholt managed their extensive landholdings and livestock resources during the early modern period.

Finally, comparative research examining livestock management at elite centers across different North Atlantic regions could provide valuable perspectives on how similar institutions adapted to diverse environmental and economic contexts. By comparing Skálholt with ecclesiastical establishments in Denmark, Norway, or the Faroe Islands, future research could develop more nuanced understanding of how elite institutions mediated between local adaptations and broader European influences across the North Atlantic region during this transitional period.

7.7 Conclusion

The biometrical analysis of livestock remains from Skálholt has revealed distinctive management strategies that distinguish this elite ecclesiastical center from

ordinary Icelandic farms during the early modern period. The evidence suggests that Skálholt implemented specialized approaches that balanced traditional Icelandic adaptations with selective innovations, creating distinctive morphological signatures in both cattle and sheep assemblages. These patterns reflect not simple environmental adaptation but deliberate management strategies aligned with specific institutional priorities and economic objectives.

For cattle, the evidence indicates specialized management practices potentially oriented toward beef production – unusual within Iceland's predominantly dairy-focused economy. The distinctive pattern of metacarpal dimensions suggests the potential presence of males (either bulls or steers) within the assemblage, while evidence for both naturally and artificially polled specimens indicates selective breeding for specific traits rather than wholesale breed replacement. This approach demonstrates sophisticated engagement with European breeding innovations, yet implemented within Iceland's established cattle population in ways that maintained adaptations to local environmental constraints.

For sheep, the biometrical analysis reveals compelling evidence for specialized wether management focused on wool production. The distinctive relationship between length and width dimensions, combined with reduced measurement variability, suggests standardized management practices aligned with Skálholt's documented status as a major landowner with extensive sheep holdings. The maintenance of wether flocks would have enhanced wool production – a cornerstone of Iceland's economic system during the seventeenth and eighteenth centuries – while reinforcing Skálholt's position within regional economic networks.

When situated within broader North Atlantic contexts, these findings reveal complex patterns of regional adaptation that challenge simplistic narratives of agricultural improvement. Rather than directly emulating English agricultural models focused on dramatic size increases through new breed introductions, Skálholt appears to have engaged selectively with improvement concepts, adapting them to Iceland's distinctive environmental constraints and economic priorities. This regionally specific approach to agricultural innovation represents a sophisticated response to both European influences and Icelandic realities during a period of significant agricultural transition.

The biometrical patterns documented at Skálholt contribute to theoretical discussions regarding agricultural adaptation, technology diffusion, and human-environment interactions in marginal landscapes. By revealing how this elite institution navigated the complex interplay between environmental constraints, cultural traditions, and external influences, this research challenges deterministic models and highlights the agency of local institutions in shaping agricultural practices. The evidence supports more nuanced theoretical frameworks that accommodate multiple causal factors, diverse adaptive pathways, and sophisticated decision-making processes in agricultural development.

In conclusion, Skálholt's livestock management strategy exemplifies what might be termed "calibrated improvement" – enhancing specific aspects of traditional systems while maintaining core adaptations to local conditions. This sophisticated approach, made possible by Skálholt's institutional resources and knowledge networks, demonstrates how elite ecclesiastical centers could function as mediators

between local traditions and external innovations during periods of agricultural transition. By revealing these patterns through integrated biometrical analysis situated within broader historical and environmental contexts, this research contributes to our understanding of the complex relationships between human societies and their environments across both time and space.

Appendix 1

North Atlantic Bone Measurement Database

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