

Norse Animal Husbandry in Liminal Environments: Stable Isotope Evidence from the Scottish North Atlantic Islands

Jennifer R. Jones & Jacqui A. Mulville

To cite this article: Jennifer R. Jones & Jacqui A. Mulville (2018): Norse Animal Husbandry in Liminal Environments: Stable Isotope Evidence from the Scottish North Atlantic Islands, Environmental Archaeology, DOI: [10.1080/14614103.2018.1439678](https://doi.org/10.1080/14614103.2018.1439678)

To link to this article: <https://doi.org/10.1080/14614103.2018.1439678>



© 2018 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



View supplementary material [↗](#)



Published online: 20 Mar 2018.



Submit your article to this journal [↗](#)



View related articles [↗](#)



View Crossmark data [↗](#)



Norse Animal Husbandry in Liminal Environments: Stable Isotope Evidence from the Scottish North Atlantic Islands

Jennifer R. Jones ^a and Jacqui A. Mulville ^b

^aDepartment of Archaeology, School of Geosciences, Aberdeen University, Aberdeen, UK; ^bDepartment of Archaeology and Conservation, School of History, Archaeology and Religion, Cardiff University, Cardiff, UK

ABSTRACT

This paper employs $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis of bone collagen to explore animal management at large Norse settlement sites in the liminal environments of the Scottish North Atlantic Islands. The Norse period was a time of social, cultural and economic change; the need to feed an expanding population and the demand for trade meant that domestic stock were a crucial resource. Our results indicate that rearing animals in these challenging insular environments required careful management. At all sites, the diet and movement of domestic cattle and sheep were highly similar and carefully controlled and, despite many of the analysed settlements lying close to the coast, there was no use of shorefront grazing or fodder resources. In contrast, pig rearing strategies varied across the island groups. In the Western Isles pig diets were diverse, indicative of household or ad hoc management, whilst on Orkney all pigs consumed a more restricted diet based primarily on terrestrial protein. A comparison of red deer with domestic stock on the Western Isles indicates that both groups were exploiting similar grazing niches.

ARTICLE HISTORY

Received 13 November 2016
Accepted 2 February 2018

KEYWORDS

Isotopes; animal husbandry;
Norse; North Atlantic Islands;
Orkney; Western Isles

Introduction

The arrival of the Vikings, and their subsequent settlement in the Scottish North Atlantic islands, produced distinct changes in population, culture and economics, including the emergence of market economies and centralised authorities (Barrett 2012; Barrett et al. 2000, 2004). The growth in the size of insular human populations generated an increased demand for food and its distribution (Barrett 2012; Barrett et al. 2000, 2001) resulting in changes in food production and food composition, and the development of market trade during the latter stages of the Norse period (Dyer 2002; Hoffmann 1996; Barrett 1997). Some of these developments are attested to within the rich archaeological evidence from sites across the Northern and Western Isles of Scotland.

To sustain the expanding Norse populations within the islands, and to provide a surplus for trade, it was necessary to produce food in sufficient quantities by rearing livestock, growing crops and fishing. The difficulties of pastoral farming in the Scottish islands, and further north, and the challenges of finding suitable fodder for animals in these liminal environments has been debated at depth; see for example, the discussion by Mulville, Bond, and Craig (2005) of high levels of cattle infant mortality in prehistoric island assemblages. The critical link between animal management and economic

success is attested elsewhere in the Norse diaspora, with contemporary farmsteads in Iceland ranked according to their 'fodder reserve value' and the ability to maintain stock over the harsh winter months (Amorosi et al. 1998).

The importance of fishing is evidenced by an increase in the numbers of fish recovered from archaeological sites, with a rise in the consumption of marine resource also demonstrated by isotopic analysis of human remains ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) (Barrett, Nicholson, and Cerón-Carrasco 1999, 2001; Barrett and Richards 2004; Colley 1983; Harland 2006; Ingrem 2005; Richards, Fuller, and Molleson 2006) and the presence of fish residues within pottery (Cramp et al. 2014). This dietary diversification indicates a greater resource base being exploited, and is probably related to the change in population in the islands during this period.

Whilst wild resources, other than fish, did not form a significant part of food production the intensification of food production and procurement would have had an effect on wild species. For example, red deer would have been subject to increasing habitat loss and disturbance as well as a possible increase in hunting pressure. These impacts may have led to changes in cervid behaviour and may be linked to the population decline and eventual eradication of red deer in Orkney during the Norse period (Mulville 2010).

CONTACT Jacqui A. Mulville Mulvilleja@cardiff.ac.uk

Supplemental data for this article can be accessed here <https://doi.org/10.1080/14614103.2018.1439678>

© 2018 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To explore changes in stock management and wild mammalian species ecologies during the Norse period this paper draws upon stable isotope analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of faunal bone collagen at four sites in Orkney and the Western Isles. Bone collagen isotopic analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ provides direct evidence of the protein part of mammalian diet over timescales that typically represent a significant proportion of an individual's life (e.g. 10–15 years for a human, Chisholm, Nelson, and Schwarcz 1982; Schoeninger, De Niro, and Tauber 1983; Schoeninger and De Niro 1984; DeNiro 1985). In the Scottish islands the technique has commonly been used to explore past human diets (Richards and Mellars 1998; Schulting and Richards 2002; Schulting et al. 2010; Richards, Fuller, and Molleson 2006) and more recently has been employed to understand landscape use within insular animal assemblages (Jones and Mulville 2016; Jones et al. 2012; Madgwick et al. 2012a). As cattle and sheep have similar metabolisms they are isotopically indiscernible if consuming similar diets (Hofmann 1989; Van Soest 1984) and any variation in their isotopic values is therefore likely to be indicative of differences in management of the two species. A number of key landscape indicators have also been developed that are useful for identifying the consumption of shorefront resources. Grazing in coastal locations has been linked to an increase in $\delta^{15}\text{N}$ values (Britton, Müldner, and Bell 2008) whilst $\delta^{13}\text{C}$ values can be altered by salinity levels (Guy, Reid, and Krouse 1986a, 1986b; van Groenigen and van Kessel 2002) allowing, for example, coastal grazing in 1–15th century AD sheep on the Flemish Coastal plain to be identified (Müldner, Britton, and Ervynck 2014). For omnivorous food species, isotopic analysis can identify elevated $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values associated with the consumption of marine protein, for example within Iron Age pig specimens in the Western Isles (Jones and Mulville 2016).

Research Aims

This research explores animal husbandry, management and ecologies within the challenging insular conditions posed in the Scottish North Atlantic Islands during a crucial period of Norse social and economic development (800 to 1400 cal. AD). This is achieved by comparative analysis of bulk bone collagen stable isotope ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) of fauna from Norse period sites across three island groups: The Western Isles, Orkney and Shetland. These closely dated assemblages permit chronological comparison within the Norse period, and spatial comparison between the different island groups. Both domestic (cattle, sheep, and pig) and wild species (red deer) will be investigated to explore the impact of the Norse on the agricultural and natural environment throughout this period.

The following research questions will be addressed; How were domestic animals managed during the Norse Period?

What was the role of shorefront resources in stock management?

Are there chronological difference in the management of animals?

Are similar management strategies employed by the Norse across the North Atlantic islands?

The sites

This study examines animals from Norse sites spanning the archipelagos of the Western Isles (also known as the Outer Hebrides), Orkney and Shetland. These archipelagos lie off the West and North coasts of Scotland with the constituent islands varying in size. Within this study the sites are located on the larger insular land masses (Figure 1): Bornais and Cille Pheadair are both found on South Uist (32k ha), in the Western Isles, Earl's Bu is on Mainland, Orkney (52k ha) and Jarlshof lies on Mainland, Shetland (98k ha). The islands all have different lithologies but have a similar maritime climate, with relatively low, stable temperatures, high winds and high rainfall.

The North Atlantic Islands have been affected by a combination of sea level change and coastal erosion, resulting in the exposure and the destruction of archaeological sites in the islands (Hansom 2005). Today all of the sites analysed lie on, or near to, the coast due to the effects of isostatic sea level change but as sea levels were

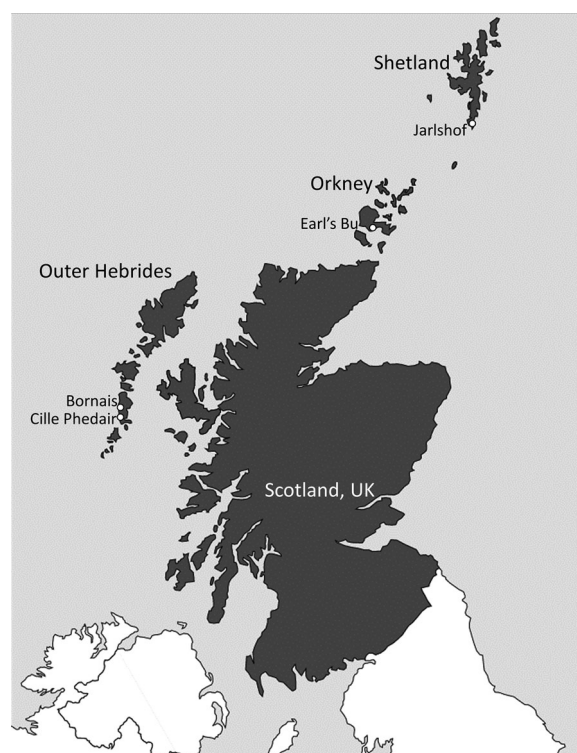


Figure 1. Map of the Scottish Islands showing the key Norse sites analysed in this study.

Table 1. Table of dates and phases of the four Norse sites included in this study, including the number of samples taken from each phase.

Site	Phase	Date range of site/ phase	No. of bones sampled				References
			Cattle	Sheep	Pig	Red deer	
Bornais, Outer Hebrides	Early Norse	800–1040 cal. AD	9	3	4	10	Sharples (<i>forthcoming</i>), Mulville et al. (2009)
	Middle Norse	1150–1290 cal. AD	6	4	1	4	
	Late Norse	1290–1410 cal. AD	9	5	6	3	
	Totals		24	12	11	17	
Cille Phedair, Outer Hebrides	Middle Norse, Phase 3	1030–1140 cal. AD		2		1	Parker Pearson et al. (2018)
	Middle Norse, Phase 4				1		
	Middle Norse, Phase 5		7	4	7	6	
	Middle Norse, Phase 6			1			
	Totals		7	7	8	7	
Jarlshof, Shetland	Earlier Norse	850–1000 AD	3				Hamilton (1956)
	Later Norse	1000–1300 AD	4	7			
	Totals		7	7			
Earl's Bu, Orkney	Earlier Norse	Mid 800s–Mid 1100s AD	7	8	6	1	Mainland et al. (2016), Batey (2003)
	Later Norse		8	7	7		
	Totals		15	15	13	1	
	Grand totals		53	41	32	25	

lower in the past (up to 5 m, de la Vega-Leinert, Smith, and Jones 2007) the sites of Bornais, Cille Phedair in the Western Isles, and Earl's Bu in Orkney were likely further inland than their current locations suggest.

A summary of the Norse phases of occupation at each of these sites and available dating evidence is displayed in Table 1. All sites are discussed in terms of the phases assigned to them in the original records and site reports.

Bornais, Western Isles

Bornais is a large Iron Age to Norse period settlement on South Uist. The site comprises around twenty buildings, preserved as a number of mounds (numbered 1, 2, 2a and 3) within the machair (a band of low-lying coastline on the west of the islands formed of calcareous shell sand), and is one of the largest Norse period settlements in the North Atlantic region (Sharples 2005). The site has Iron Age antecedents and the Norse occupation dates from 10th–14th century AD. Norse occupation of the site is broadly split into three chronological periods; Early (800–1040 cal. AD), Middle (1040–1290 cal. AD) and Late (1290–1400 cal. AD). Phasing at Bornais is based on posterior density estimates at 68% probability (Sharples *forthcoming*).

The site yields extensive zooarchaeological remains relating to the Norse period occupation, with cattle, sheep and then pig dominating the faunal assemblage (Mulville and Powell *forthcoming*). Previous isotopic analysis has been completed on Iron Age and Late Iron Age material from the site, in addition to a small number of Norse specimens (Jones and Mulville 2016; Madgwick et al. 2012a; Mulville et al. 2009). The 43 newly analysed Norse animal bone specimens from Bornais are here combined with the results from 21 specimens analysed by Mulville et al. (2009) producing a dataset of 64 specimens for the site.

Cille Phedair, Western Isles

Cille Phedair is a Norse settlement site located 10 km to the south of the site of Bornais on the island of South Uist in the Western Isles. The site contained structures of four long houses, and is much smaller in size than Bornais. The occupation of the settlement spans between 1000 and 1220 cal. AD. The zooarchaeological record at Cille Phedair is dominated by sheep, with cattle being the second most commonly represented species, followed by pig and to a lesser extent red deer.

In this study a total of 33 domestic animal bone specimens were analysed. The majority (n = 29) were derived from phase 5, with an additional two specimens from phase 3, and one specimen each from phases 4 and 6, which all date to between 1030 and 1140 cal. AD (phasing based on posterior density estimates at 68% probability) (Parker Pearson et al. 2018). Phases 4–6 are contemporaneous with the Middle Norse period at Bornais.

Earl's Bu, Orkney

The site of Earl's Bu, in Orkney, was a residence and associated manorial farm complex of the Orkney Earl's, the highest-ranking nobility in the islands, who were highly influential and well connected across the reach of the Scandinavian world. The site would have played an important role in meetings and feasting for the Earls and their associates (Crawford 2013; Batey 2003; Mainland et al. 2016). The site dates from AD late 800s–mid 1100s; two main phases, an Earlier and a Later phase of occupation have been identified (Batey 2003). Domestic species predominate at the site with cattle most abundant, a characteristic observable in Norse sites across Orkney (and indeed the Western Isles) (Mainland 1995; Bond 2007a; McGovern et al. 2009). A

total of 22 specimens were sampled from Earl's Bu from the two phases of occupation at the site, including a single red deer specimen from the Earlier phase.

Jarlshof, Shetland

Jarlshof in Shetland is a multi-period site with archaeological evidence from the Neolithic through to the Medieval period. There is a small faunal assemblage from a Norse settlement site recovered during the excavations in the 1950s. The zooarchaeological archive was separated into two phases of occupation at the settlement, corresponding to AD 850–1000 and AD 1000–1300 (Hamilton 1956), referred to as the Earlier and Later Norse periods respectively. Only three cattle specimens were available from the Earlier Norse period at the site. A further four cattle, and seven sheep from the Later Norse period at the site were also sampled.

Analytical methodology

Mature animal specimens, as determined from epiphyseal fusion and surface texture (Silver 1969), were selected for analysis to avoid nursing signatures as these can cause inflated $\delta^{15}\text{N}$ values (Schurr 1997, 1998). Different individuals were targeted by sampling the same skeletal elements from the same side of the body. Typically, bones with denser cortical thickness, and thus greater quantities of collagen such as the tibia, femur, radius and humerus were selected.

Collagen extraction was attempted on 129 specimens at the Cardiff University Bioarchaeology Laboratory following a modified Longin method (Longin 1971; Collins and Galley 1998). Bone fragments between 0.7 and 0.9 g were drilled and cleaned using aluminium oxide air abrasion. Samples were demineralised in 0.5 M HCL at 6–8°C for between 3 and 10 days. Specimens were washed three times using deionised water before being gelatinised in a weak acidic solution (pH 3 HCL) at 70°C for 48 h. Samples were filtered using 5–8 μm biological filters (Evergreen Scientific, California, USA).

Isotopic analysis of specimens from Jarlshof, Cille Phedair and Earl's Bu was funded by, and undertaken at the NERC Life Sciences Mass Spectrometry Facility in East Kilbride, UK. The extracted collagen was combusted using an ECS 4010 elemental analyser (Costech, Milan, Italy), coupled to a Delta V Plus isotope ratio mass spectrometer (Thermo Scientific, Bremen, Germany).

Analysis of specimens at Bornais from Mound 2 and 2a was undertaken at the Dorothy Garrod laboratory for stable isotope analysis at the McDonald Institute, Cambridge, UK, using a Costech elemental analyser coupled to a Finnigan MAT253 mass spectrometer. The results are presented alongside the 21 specimens that were generated by Mulville et al. (2009), which were also prepared at Cardiff University using the same

methodology, and were analysed at the Cambridge University facility, enabling comparability of results.

The $\delta^{13}\text{C}$ values and $\delta^{15}\text{N}$ values are reported relative to the V-PDB and AIR standards. Based on replicate analysis of in-house laboratory standards, analytical error was 0.1 ‰ for $\delta^{13}\text{C}$ and 0.2 ‰ for $\delta^{15}\text{N}$ (1 σ). Mann–Whitney U test was used for statistical analysis, with a post-hoc Holm–Bonferroni correction (Holm 1979) using the ecological statistical programme 'PAST' (Hammer, Harper, and Ryan 2001). A *p*-value of .05 or less was deemed to be indicative of a statistically significant result.

Results and Interpretation

The results for each of the sites are presented individually, discussing the management/ecology of each species. Due to differences in the dating of phases between the sites, and because of geographical differences in isotopic values observed between the island groups (Jones et al. 2012) direct comparisons of individual isotopic values between sites in Orkney and the Outer Hebrides are not used. Each site is considered individually to facilitate the diachronic comparison of the isotopic values of species within each phase of occupation. The newly generated results from Bornais are combined with data from Mulville et al. 2009 to enhance interpretation at this site.

Preservation within the sites was exceptional, with only 2 of the 131 specimens newly analysed specimens yielding insufficient collagen for analysis, these were two cattle from Cille Phedair (KIL04 and KIL17). All specimens fell within the accepted atomic C:N value range of 2.9–3.6 (as stated by DeNiro 1985), indicative of *in vivo* collagen, with 103 specimens having C:N values between 2.9 and 3.4 complying with the more rigid criteria of van Klinken (1999). The specimens also typically had %C values above 35% and %N values above 10%, again indicative of well-preserved collagen. All values and quality indicators are included in the supplementary dataset.

Discussion of the results follows, comparing each site considered individually to facilitate the diachronic comparison of the isotopic values of species within each phase of occupation.

Bornais

Cattle at Bornais reveal little variation in $\delta^{13}\text{C}$ values through time, with similar mean values for the Early ($\delta^{13}\text{C}$ -21.7 ‰ \pm 0.5, 1 σ), Middle ($\delta^{13}\text{C}$ -21.4 ‰ \pm 0.4, 1 σ) and Late Norse phases ($\delta^{13}\text{C}$ -21.4 ‰ \pm 0.3, 1 σ) (Table 2). The Early Norse cattle occupy a slightly larger range in $\delta^{13}\text{C}$ values (Early; -22.7 ‰ to -21.7 ‰, Middle; -20.3 ‰ to -21.8 ‰, Late; -22.0 ‰, to -21.0 ‰,) (Table 2; Figure 2). The majority of the cattle $\delta^{15}\text{N}$ values range between 3.7 and 6.2 ‰ (Figure 2);

two individuals with higher values of 8.6 ‰ and 9.6 ‰, have been previously identified as potentially being juvenile individuals with nursing signatures (Mulville et al. 2009) (Figure 2). There were no statistically significant differences observed for the cattle between the temporal periods for $\delta^{13}\text{C}$ (Early/Middle $p = .08$ Middle/Late $p = .95$, Early/Late $p = .12$) or $\delta^{15}\text{N}$ (Early/Middle $p = .08$, Middle/Late $p = .24$, Early/Late $p = .40$).

The sheep mean values are also similar, with $\delta^{13}\text{C}$ values for Early, Middle and Late periods lying within 0.2 ‰ of each other (Table 2; Figure 2). The range for sheep in each phase of occupation is comparable; Early; -21.6 ‰ to -21.1 ‰, Middle; -21.8 ‰ to -20.5 ‰, and Late; -21.6 ‰ to -21.4 ‰, and no statistically significant differences between the periods were observed (Early/Middle $p = .85$, Middle/Late $p = .71$, Early/Late $p = .55$). The sheep mean $\delta^{15}\text{N}$ value was slightly higher in the Early period (Early 5.3 ‰ ± 0.3 1 σ , Middle 4.9 ‰ ± 0.5 1 σ , Late 4.8 ‰ ± 0.1 1 σ), although no statistically significant differences were observed (Early/Middle $p = .59$, Middle/Late $p = .90$, Early/Late $p = .55$). Overall the Bornais cattle and sheep show similarity in both ranges and means (Table 2), with no distinguishable difference between the diets of either species.

For the red deer there was little change in $\delta^{13}\text{C}$ values through time with mean values for the Early,

Middle and Late period being -21.6 ‰ ± 0.2 , 1 σ (0.1, 1 σ for Middle) (Table 2; Figure 2). The red deer have higher mean $\delta^{15}\text{N}$ values in the Middle Norse, although no statistically significant differences were observed (Early/Middle $p = .26$, Middle/Late $p = .38$, Late/Early $p = .93$) between phases. The values for red deer overlap with those for the domestic herbivores (Table 2; Figure 2).

There is a high diversity in the isotopic values of the pigs analysed at Bornais (Figure 2). Two Early Norse and a single Late Norse individual have stable isotopic signatures consistent with a marine protein dietary component (a, b and c in Figure 2). The single Middle Norse specimen had isotopic signatures consistent with the consumption of terrestrial protein, plotting in the middle of the herbivores ($\delta^{13}\text{C}$ -20.4 ‰, $\delta^{15}\text{N}$ 7.8 ‰) whilst other Late Norse pigs exhibited isotopic signatures consistent with a mixed terrestrial protein and plant diet (Figure 2).

Cille Phedair

The bulk of specimens from Cille Phedair were from phase 5 of the site (Table 1). As observed at Bornais, sheep and cattle occupy similar ranges in $\delta^{13}\text{C}$ values (cattle; -22.1 ‰ to -21.2 ‰, sheep; -21.8 ‰ to -21.5 ‰), and $\delta^{15}\text{N}$ values (cattle; 3.7 to 5.8, sheep;

Table 2. Summary statistics of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for each phase within the Norse North Atlantic sites of Bornais, Cille Phedair, Earl's Bu and Jarlshof. Values for Bornais include Values for Bornais include individuals analysed by Mulville et al. 2009.

			n=	$\delta^{13}\text{C}$				$\delta^{15}\text{N}$			
				Mean	Min	Max	1 σ	Mean	Min	Max	1 σ
Bornais, Outer Hebrides	Early Norse	cattle	6	-21.7	-22.7	-20.9	0.5	4.6	3.7	5.3	0.5
		sheep	3	-21.3	-21.7	-21.1	0.3	5.3	4.8	6.1	0.7
		pig	4	-19.6	-21.5	-17.6	1.6	9.4	6.1	11.4	2.3
		red deer	10	-21.6	-22.0	-21.2	0.2	5.1	4.3	6.1	0.6
	Middle Norse	cattle	9	-21.3	-21.8	-20.8	0.4	6.4	4.2	9.6	2.2
		sheep	4	-21.3	-21.8	-20.5	0.5	4.9	3.4	6.0	1.2
		pig	1	-20.4	-	-	-	7.8	-	-	-
		red deer	4	-21.6	-21.8	-21.4	0.2	5.7	4.9	6.6	0.7
	Late Norse	cattle	9	-21.4	-22.0	-21.0	0.3	4.9	4.2	5.8	0.6
		sheep	5	-21.5	-21.6	-21.3	0.1	4.8	4.2	5.3	0.4
		pig	6	-20.5	-21.5	-19.3	0.8	7.9	7.1	8.9	0.8
		red deer	3	-21.6	-21.8	-21.5	0.1	5.1	4.8	5.4	0.3
	Phase 5	cattle	5	-21.5	-22.1	-21.2	0.3	4.6	3.7	5.8	0.9
		sheep	4	-21.6	-21.8	-21.5	0.2	5.3	3.8	6.0	1.0
		pig	7	-20.0	-21.9	-17.8	1.5	8.0	4.8	11.3	2.1
		red deer	6	-21.9	-22.1	-21.6	0.2	5.4	4.0	6.9	1.1
Cille Phedair, Outer Hebrides	Phase 3	sheep	2	-21.3	-21.1	-21.4	-	5.7	5.2	6.2	-
		red deer	1	-21.6	-	-	-	6.0	-	-	-
	Phase 4	pig	1	-21.0	-	-	-	7.9	-	-	-
	Phase 6	Sheep	1	-21.3	-	-	-	4.6	-	-	-
	Earlier phase	cattle	7	-21.9	-22.2	-21.6	0.3	5.7	5.1	6.2	0.4
		sheep	8	-21.8	-22.0	-21.6	0.2	6.0	4.9	7.5	0.8
		pig	6	-20.8	-21.3	-19.8	0.6	8.2	5.2	9.2	1.5
		red deer	1	-20.5	-	-	-	5.2	-	-	-
	Later Phase	cattle	8	-21.5	-22.0	-21.3	0.3	5.7	5.3	6.5	0.4
		sheep	7	-21.6	-22.0	-21.3	0.3	5.9	4.8	6.8	0.6
		pig	7	-21.7	-22.1	-21.3	0.3	9.0	7.8	11.3	1.2
Earl's Bu, Orkney	Early Norse	cattle	3	-21.1	-19.8	-20.2	0.8	5.5	7.3	6.4	0.9
		sheep	4	-21.5	-21.7	-21.0	0.3	5.3	4.7	5.6	0.4
	Later Norse	cattle	4	-21.5	-21.7	-21.0	0.3	5.3	4.7	5.6	0.4
		sheep	7	-21.5	-21.7	-21.1	0.3	5.4	3.7	6.5	1.1
Jarlshof, Shetland	Early Norse	cattle	3	-21.1	-19.8	-20.2	0.8	5.5	7.3	6.4	0.9
	Later Norse	cattle	4	-21.5	-21.7	-21.0	0.3	5.3	4.7	5.6	0.4

Note: Mean values for each species are displayed in bold.

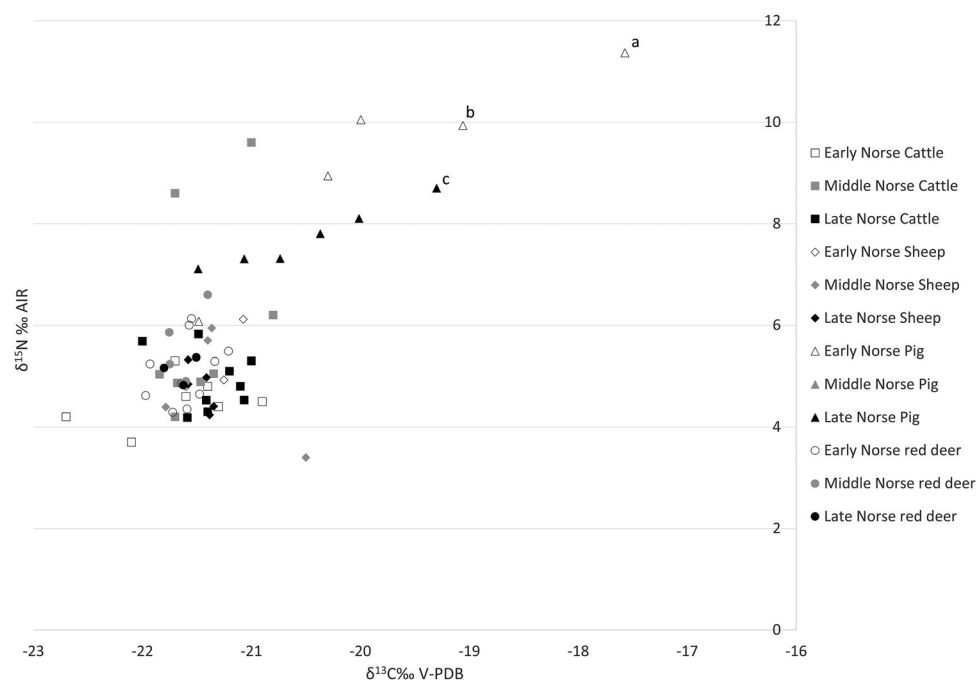


Figure 2. Bornais $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from animal specimens from cattle, sheep, pig and red deer specimens sampled from Early, Middle and Late phases of occupation at the site. Points a, b and c are individuals referred to in the text that show evidence of marine protein consumption.

3.8 ‰ to 6.0 ‰) (Table 2). There is no statistically significant difference in the cattle or sheep populations in the $\delta^{13}\text{C}$ ($p = .93$) or $\delta^{15}\text{N}$ values ($p = .39$) observed.

The red deer values are similar to the domestic herbivores, although they exhibit slightly lower $\delta^{13}\text{C}$ values ranging between to -22.1 ‰ to -21.6 ‰. No statistically significant difference was observed between the red deer $\delta^{13}\text{C}$ and cattle ($p = .08$) populations. A statistically significant difference was observed between

the sheep and the red deer ($p = .01$), with red deer being typically having lower $\delta^{13}\text{C}$ values. No difference in $\delta^{15}\text{N}$ was observed between red deer and any of the herbivores analysed (with sheep $p = .70$ and with cattle $p = .32$).

Within the pigs, three samples have elevated $\delta^{15}\text{N}$ values indicative of higher levels of protein consumption (Figure 3), and in this they are similar to some of the individuals from Bornais. A further

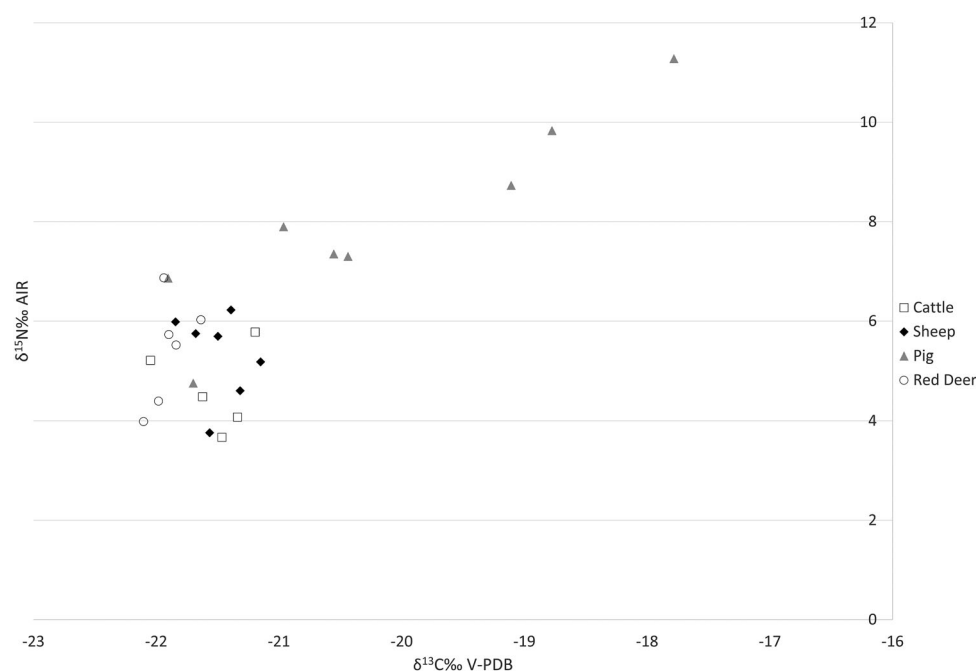


Figure 3. Cille Phedair $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from cattle, sheep, pig and red deer specimens sampled from Middle Norse period occupation of the site.

two individuals had lower $\delta^{15}\text{N}$ values associated with a diet lower in protein. These results demonstrate a diversity in pig management strategies during phase 5.

Earl's Bu

The cattle $\delta^{13}\text{C}$ values at Earl's Bu for the Earlier phase ranged between -22.2 ‰ and -21.6 ‰, and for the Later phase -22.0 ‰ and -21.3 ‰ (Table 2, Figure 4), with a statistically significant difference between the populations observed ($p = .04$). The range of $\delta^{15}\text{N}$ values during the Earlier phase was 5.1 ‰ to 6.2 ‰ and for the later phase 5.3 ‰ to 6.5 ‰, no statistically significant difference was observed ($p = .95$).

Sheep occupy exactly the same ranges as the cattle in terms of the $\delta^{13}\text{C}$ values observed (Table 2, Figure 4), and no statistically significant difference between sheep in either phase of the site was observed ($p = .08$). The sheep have a higher range of $\delta^{15}\text{N}$ values in the early phase (4.9 ‰ to 7.5 ‰), compared to the later (4.8 ‰ to 6.8 ‰), but these differences were not statistically significant ($p = .95$).

The pigs at Earl's Bu fall into two distinctive groups of $\delta^{13}\text{C}$ values (Figure 4), with the Early Norse animals having higher values (range -21.3 ‰ to -19.8 ‰) than the Later Norse individuals (range; -22.1 ‰ to -21.3 ‰). There is no overlap between the populations and this difference was statistically significant ($p = .00$). Earlier Norse pigs also typically had lower $\delta^{15}\text{N}$ values, (range 5.2 ‰ to 9.2 ‰), compared to higher values observed in the Later phase (range 7.8 ‰ to 11.3 ‰), although there was no statistically significant difference between these time periods observed ($p = .94$).

The single red deer specimen derives from the Earlier Norse phase and has a higher $\delta^{13}\text{C}$ value (-20.5 ‰) than the other herbivores at the site.

Jarlshof

A single Early phase cattle specimen had an isotopic value of -21.1 ‰ $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of 5.5 ‰, suggesting no saline or coastal dietary input however two other specimens are notable for their higher $\delta^{13}\text{C}$ (both -19.8 ‰) and $\delta^{15}\text{N}$ values (6.3 ‰ and 7.3 ‰) (Table 2; Figure 5). These higher values are indicative of shorefront grazing, or the consumption of shore-front resources, with salinity affecting the $\delta^{13}\text{C}$ value. The Later phase cattle had $\delta^{13}\text{C}$ values ranging between -21.7 ‰ and -21.0 ‰, and $\delta^{15}\text{N}$ values ranging between 4.7 ‰ and 5.6 ‰, indicative of no saline input.

All sheep analysed derived from the Later Norse phase and had a small range of $\delta^{13}\text{C}$ values (-21.7 ‰ to -21.1 ‰), mirroring the range of the Later Norse cattle (-21.7 ‰ to -21.0 ‰). The sheep had higher range in $\delta^{15}\text{N}$ values (3.7 ‰ to 6.5 ‰), than the cattle (4.7 ‰ to 5.6 ‰), although no statistically significant difference between cattle and sheep within this phase were observed for either isotope ($\delta^{13}\text{C}$ $p = .92$, $\delta^{15}\text{N}$ $p = .64$).

Discussion

The results from the stable isotopes are combined to provide an overview of the domestic and wild animal management and ecologies on the islands during the Norse period. The discussion is framed by exploring the management of individual species within each island group, before any temporal and spatial

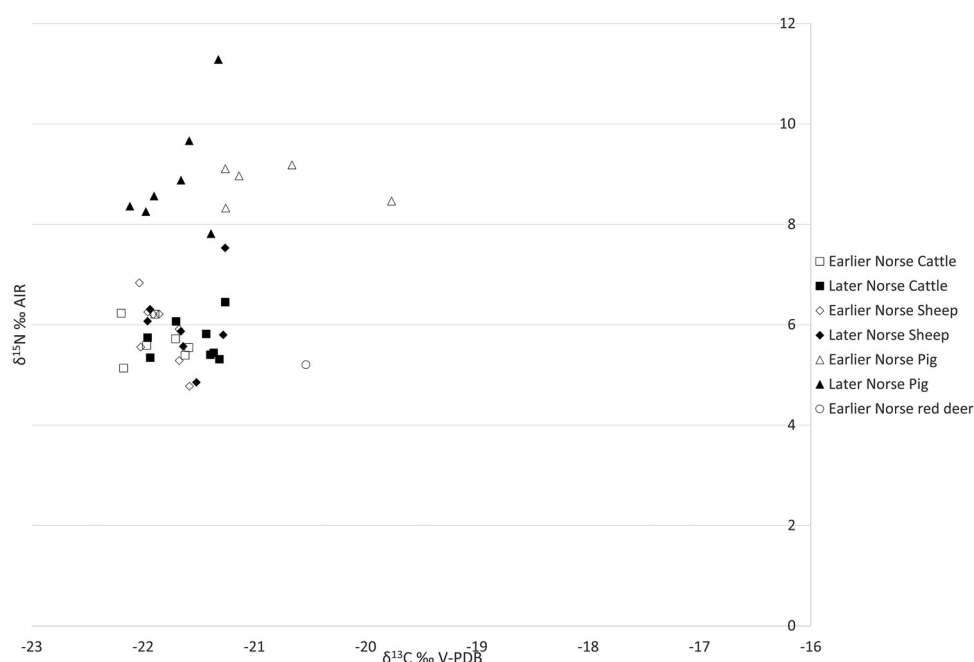


Figure 4. Earl's Bu $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from cattle, sheep, pig and red deer specimens sampled within the Earlier and Later Norse phases at the site.

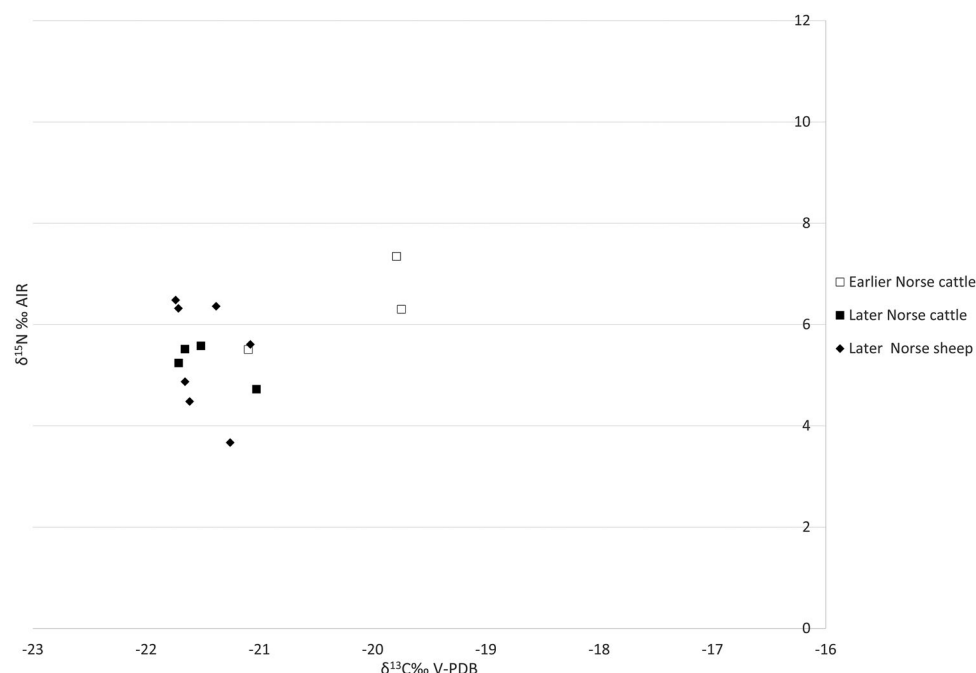


Figure 5. Jarlshof $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from cattle and sheep specimens sampled from the Earlier and Later Norse period phases of the site.

variations in the management of each species between different phases of Norse occupation are considered.

Cattle management

The stable isotope results derived from cattle on the Western Isles sites indicate a herbivorous diet. None of the cattle exhibit elevated $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values that are typically associated with the consumption of coastal plants or plant material growing in saline environments (Britton, Müldner, and Bell 2008; Müldner, Britton, and Ervynck 2014; Jones and Mulville 2016). The isotopic values suggest that cattle at both Bornais and Cille Phedair were grazed at some distance from the coastline and/or maritime plant communities and were not free to roam and exploit coastal resources.

Today both Bornais and Cille Phedair are located on machair close to the sea, however as noted above, erosion has substantially changed the coastline (Hansom 2005) and during the Norse period these settlements probably lay at some distance from the coast. Zooarchaeological evidence suggests that small, possibly milking, herds were kept close to the settlements throughout the year (Mulville and Powell 2012, 233). Milk was a critical resource, with dairy lipid residues present in the entire suite of pottery vessels analysed from the Norse phases at these sites (Cramp et al. 2014). Whilst other stock were probably kept away from local fields, at least during the crop growing season (see below), the isotopic evidence suggests that these pastures were not coastally located. Historically there is evidence of transhumance, with

machair based cattle taken to the interior hills during summer (Smith 2012) and the isotopic values indicate that this pattern of stock movement could have occurred during the past. At Bornais the similarity of the cattle $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values across time points to identical types of pasture and fodder sources being exploited throughout the duration of occupation. Thus the Norse were employing a persistent and developed pattern of centralised management of cattle, with animals being herded together systematically in a highly organised fashion.

At Jarlshof in Shetland two of the three Early Norse cattle sampled had elevated $\delta^{13}\text{C}$ values possibly indicative of shorefront grazing. Whilst the Shetland coastline has also suffered from coastal erosion the site of Jarlshof was always situated close to the sea (Hamilton 1956) and animals could have been feeding on saline pastures close to the settlement. At this site, the close husbanding of cattle may have been associated with milk production, but the single individual with lower $\delta^{13}\text{C}$ values suggests that not all animals were husbanded in this manner.

At Earl's Bu, currently c. 200 m from the coastal front of Ophir, Orkney the $\delta^{13}\text{C}$ values of all 15 cattle sampled indicate that they were raised away from the shorefront, in both the Earlier and Later periods, with no evidence of aquatic plant consumption, or a saline influence. This isotopic analysis of bone supports cattle tooth analysis at Earl's Bu where $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and dental microwear analysis provided no evidence of shorefront grazing (Mainland et al. 2016). The lack of access to coastal resources suggests that the cattle movement in the landscape

was highly controlled. However, whilst there is no evidence of coastal foods at Earl's Bu there are higher cattle $\delta^{13}\text{C}$ values within the later Norse phase. This could be indicative of a change in pasturing regimes over time, as a response to climatic change, an intensification of stock rearing or simply changes in land ownership and access with different pastures being acquired and used for grazing. These changes could be related to a degradation of pastures in the late Norse period, in Greenland a decline in pasture viability and over-grazing at this time has been identified (Mainland 2006). For both phases the isotope values for cattle at Earl's Bu suggest a centralised herding system, with animals within each phase exhibiting standardised diets.

Norse Sheep Management

No sheep from the Western Isles, or Orkney, provided evidence of the elevated $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values associated with feeding in shorefront locations. Congruent research on sheep teeth $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ and dental microwear also indicate that shorefront resources were not exploited at Earl's Bu in Orkney (Mainland et al. 2016). This is surprising given that in prehistory, from the Neolithic onwards in Orkney and from the Bronze Age in the Western Isles, bulk collagen isotopic analysis has demonstrated that the shorefront was routinely used as a foddering location for sheep (Jones and Mulville 2016), in addition to being identified using incremental tooth analysis of Neolithic and Bronze Age sheep in Orkney (Balasse, Mainland, and Richards 2009, 2006).

A low diversity in isotopic values was observed within all of the sites analysed. This lack of variety in diet is unusual given what is known about sheep feeding behaviour. Ethological studies of free roaming sheep in Scotland indicate that they naturally select a diverse range of grasses and forbs (Bullock 1985; Grant et al. 1985). Therefore, unrestricted flocks would be expected to exhibit a wide range of isotopic values. The uniformity of values suggests that, unlike the prehistoric flocks (where a greater diversity in values is seen – see Jones and Mulville 2016), the movement of sheep was controlled, and animals did not regularly partake in shorefront grazing.

The overall lack of temporal change in sheep values between the Norse occupation phases, at each of the sites over 600 hundred years, suggests that the same resources (i.e. foddering materials and pasturing locations) continued to be used in the management of this species throughout this period. Thus, particular tracts of land, used for grazing stock, may have been under the control of each site for a long duration, a common characteristic observed across all three island groups.

Management of domestic herbivores in the islands: an overview

As cattle and sheep are isotopically indistinguishable, in terms of bone collagen values, there appears to have been a commonality in pasturing locations and potentially in the fodder used to sustain the herds and flocks over the challenging winter months. Both the Western Isles, from the Late Iron Age, and Orkney, from the Norse period, have similar changes in crop production with the proportion of oats increasing and flax introduced (Bond and Hunter 1987; Bond 2007b; Barrett 2012; Summers and Bond 2012). Oats and flax were used as winter fodder for sheep and cattle and if fed under similar regimes could account for some of the uniformity in isotopic values. Further work using incremental analysis of teeth from both species would be beneficial in exploring seasonality in food regimes of herbivores during the Norse period to determine if more fine-grained differences can be observed during different times of the year.

The highly controlled and comparable movement of cattle and sheep around the landscape is suggestive of a strategy tailored to the characteristics of the Scottish North Atlantic Islands. This close management may be related to soil characteristics and crop production; the coastal machair soils found predominantly in the Western Isles, but also present in Orkney, are heavily susceptible to animal disturbance and wind erosion with the result that arable farming can be highly challenging (Smith 2012, 379). Whilst animal manuring would help to fertilise the fields, as has been previously isotopically identified in the islands during the Norse Period (Jones et al. 2012), over grazing could potentially destroy the soils. Thus controlling the movement of domestic animals would have helped to both preserve the light soils and shield crops from direct stock related damage. These results provide the first detailed evidence for the close management of grazing stock, suggesting that excluding animals from coastal fields and associated vulnerable soils, was a strategy practiced at Norse sites in the liminal environments of the Scottish North Atlantic Islands. The movement of agriculture onto the fragile machair and into the heath/blackland areas is seen during the Norse period in the Western Isles (Smith 2012), showing enhanced management of the landscape during this time. Controlling animal movements away from precious agricultural land, and into designated grazing areas would have been essential in achieving economic success.

Elsewhere across the Norse diaspora there is evidence of different foddering regimes for cattle and sheep. For example, in Iceland, Norse bone collagen isotopic analysis of domestic herbivores demonstrated that cattle were typically consuming a diet that was enriched in $\delta^{15}\text{N}$ by approximately 1 ‰ relative to

sheep (Ascough et al. 2014). This contrasts with the evidence observed within the Norse Scottish insular sites, demonstrating that economic strategies at Norse sites were tailored to the distinctive conditions experienced in different regions.

Norse Pig Management

Isotopic evidence indicates a high level of variation in pig diet and management across the islands during the Norse period with no single husbandry model in use. Pigs, as omnivores, can be fed human food, human waste, fish processing waste or less economically valuable species. At both Bornais and Cille Phedair in the Western Isles individual pigs have very different isotopic values, indicating the consumption of varying quantities of terrestrial and aquatic protein, within predominantly herbivorous diets.

Similar levels of dietary variation have been observed locally (e.g. At Dun Vulcan, Middle Iron Age broch; this included evidence of marine protein consumption, Jones and Mulville 2016), and elsewhere in prehistoric Britain (e.g. Bronze Age pigs in SW England varied in both type and level of protein consumption, Madgwick, Mulville, and Stevens 2012b) and are indicative of a piecemeal approach to feeding individual animals, potentially on a household basis. If the porcine diet does reflect small scale feeding, possibly from food or human waste, the flexibility in the diet of the pigs may reflect the variability in human diets during this time. At Bornais, isotopic analysis of Iron Age pig specimens also demonstrated the consumption of differing amounts of solely terrestrial protein (Jones and Mulville 2016) however, the introduction of marine foods in Norse levels signals a distinct change in management at this site.

Marine foddering of pigs appears to be a widespread Norse practice. There are similar elevated $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in pigs from the Icelandic sites of Sveigakot, and Hofstaði (Ascough et al. 2014) with mixed diets that included marine protein consumption also identified within pigs analysed from the later Viking occupation at Ridanäs, Gotland (Koshiba, Tykot, and Carlsson 2007), Narsaq, Vatnahverfi and Igaliku, Greenland (Nelson et al. 2012).

This increasing focus on marine fodder may be linked to the commercialisation of fishing towards the end of the Norse period. Zooarchaeological datasets (Barrett 1995; Barrett, Nicholson, and Cerón-Carrasco 1999; Colley 1983; Harland 2006), human isotopic data (Barrett and Richards 2004; Richards, Fuller, and Molleson 2006) and pottery residues (Cramp et al. 2014) all show a dramatic increase in human fish consumption (termed the 'Fish Event Horizon' Barrett, Locker, and Roberts 2004). Fish were probably traded from the isles, with evidence for the drying of *Gadidae* (cod family) species at the Norse site of Quooygrew (Harland

2006, 230; Barrett 1997), and St Boniface (Barrett 1997) in Orkney from at least AD 13th and 14th C. During the Middle and Late Norse period herring fishing increases dramatically the Western Isles (Ingrem 2005), and pig isotopic values appear to mirror the associated changes in human diet and trade.

Trading of marine foods in the Norse period has been interpreted as a method of exerting and maintaining chiefly authority, enabling centralised markets to be developed at the end of the Norse period (Perdikaris 1999). The emergence of these market economies may be linked to changes in the the management of pigs at Bornais, and at a range of contemporary Norse sites, with fish waste from trade used as porcine fodder.

This pig husbandry model of variable feed strategies that incorporating marine foods did not occur at all Norse sites. At Earl's Bu on Orkney there is a low variation in diet and no evidence for pig consumption of marine protein. Pigs within each phase were feeding at the same terrestrial, vegetarian, trophic level, although a shift in $\delta^{13}\text{C}$ values between pigs from the Earlier and Later phases suggests a variation in diet over time. The low range of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for each phase indicates little diversity within pig diet. This suggests a more formalised management for each time period compared to the ad hoc feeding strategies observed in the Western Isles.

It is likely that the site status and function at Earl's Bu was a contributing factor in the management of pigs. Thus, whilst Cille Phedair, and Bornais, were typical farmsteads, Earl's Bu was a manorial estate and, along with the Brough of Birsay, Orkney, another earldom estate, had higher numbers of pigs than contemporary sites (Mainland et al. 2015). Pigs played an important role in feasting activities, a central aspect of Norse life, as practiced throughout Medieval Scandinavia and Scotland (Lucas and McGovern 2007; Woolf 2007; Zori et al. 2013). Maintaining healthy herd numbers to stock feasts would have been crucial and thus, rather than relying on piecemeal household level production, pigs were subject to formalised feeding strategies. There are other examples of this standardised management approach, for example at the Icelandic site of Hrísheimar, where isotopic analysis revealed that pigs were consuming terrestrial, vegetarian diets (Ascough et al. 2014).

No pigs were available from Jarlshof, Shetland to compare management strategies. Overall the differences in the management of pigs between the island groups indicate variability in husbandry methods and it is possible that strategies used were aligned to the function and social requirements of each site.

Red deer in the Norse period

There is only a small sample of Norse insular red deer available. In the Western Isles no changes in $\delta^{13}\text{C}$ or

$\delta^{15}\text{N}$ values were observed through time and the overlapping isotopic ranges of deer, cattle and sheep indicate that they were occupying a similar niche, located away from coastal areas. With all three species occupying a similar environmental niche it is possible red deer experienced increasing grazing pressure and disturbance from domestic stock. Red deer were exploited to a significant degree in the Norse period (Mulville 2010), as in previous periods, with both calves and adults targeted, and little evidence of a decline in population at this time.

On Orkney the single red deer specimen, from Earl's Bu, is distinct from the other herbivores due to its relatively elevated $\delta^{13}\text{C}$ value. This contrasts with all other insular red deer analysed during the Norse and preceding periods (Jones et al. 2012); these produced $\delta^{13}\text{C}$ values within the same range as the cattle sampled. The unique value for this sample may indicate a different source location for this animal. Red deer were extremely rare and potentially extinct in the Northern Isles at this point (Mulville 2010) and this single meat bearing bone may represent a traded or preserved cut of venison brought to Orkney from elsewhere.

Further work with amplified sample numbers, and including incremental dentine sampling of teeth to establish detailed life histories of red deer and domestic animals would be valuable in exploring the impact of animal husbandry practises on wild species further.

Conclusions

Our results demonstrate that, in complete contrast to prehistoric farming strategies in the islands (Jones and Mulville 2016) Norse management of herbivorous stock in both Orkney and the Western Isles was carefully controlled. Cattle and sheep were no longer free to roam the landscape. Stock animals were foddered on restricted tracts of land through time, and pastured away from the shorefront regions, despite the coastal location of many sites. Strict control of stock movement was a response to the specific conditions experienced in the Scottish Islands with both crops and fragile soils needing to be protected to sustain larger scale pastoral and arable farming. This strategy would have facilitated the production of food to support the larger population size during this period and may have enabled surpluses to be produced to allow participation in trading and market economies that emerged during the Late Norse period (Dyer 2002; Hoffmann 1996).

Pig rearing was more diverse, with different strategies in place in Orkney and the Western Isles, related to wider economic and social drivers. Pigs in the Western Isles consumed more marine foods, and this is symptomatic of the increased importance of fish for human consumption and for trade. Pigs may have been fed processing and by-catch waste

from the exploitation and preservation of herrings for trade (Ingrem 2005) as well as consuming human waste. This porcine foddering strategy mirrors that found at other farmsteads (Ascough et al. 2014; Koshiba, Tykot, and Carlsson 2007) in the wider Norse world, showing a level of connectivity between sites at this time. In contrast, the more restricted, and controlled diet of pigs at Earl's Bu, Orkney, is potentially linked to the need for this manorial Earldom to produce larger quantities of pork for feasting. Thus, animal management strategies were not centralised in the islands during this period, and varied depending on localised conditions experienced, and the needs and requirements of the individual settlements.

Further research expanding datasets and sites to include archaeological sites across the Norse diaspora would be valuable in understanding animal management and its relationship to the wider economy of Norse populations in greater depth. Expanding this research to include tooth bioapatite analysis of teeth would be beneficial to provide more detail on any potential seasonal variations in diet and foddering strategies in both domestic and wild species, and to access information on winter foddering regimes in these hostile climates. An analysis of Norse settlement sites in the wider Scandinavian world would allow us to better assess if insular animal management strategies represent a common practice, exported to the islands, or if they were tailored to the specific environmental conditions found within these liminal locations.

Acknowledgements

Richard Evershed and Lucy Cramp provided great feedback and support during project meetings throughout the course of this research. Rona McGill was invaluable in facilitating the analysis of specimens from Cille Phedair, Jarlshof and Earl's Bu. Thanks to Tamsin O'Connell and Rhiannon Stevens for facilitating the analysis of selected specimens from Bornais. Richard Madgwick, and the Cardiff Bioarchaeology class of 2010 were invaluable in helping to prepare specimens from Bornais. Thank you to Alison Sheridan at the National Museum of Scotland for her help in accessing and sampling animal bones from Jarlshof. Niall Sharples provided valuable information on the site of Bornais and facilitated access to the collection. Many thanks to Ingrid Mainland for helping us to sample the specimens from Earl's Bu. Thanks also to Mike and Karen Parker Pearson for facilitating the sampling of specimens from Cille Phedair and for providing information on phasing at the site. Thank you to Helen Smith for her insights into agricultural practises in the islands. Special thanks to the two anonymous reviews, who provided positive comments and valuable suggestions that helped to enhance the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was undertaken by the authors at Cardiff University as part of a PhD project. The authors would like to thank Natural Environment Research Council (NERC) for funding this research [grant number NE/F021054/1, PI Richard Evershed], and the NERC Life Sciences Mass Spectrometry Facility in East Kilbride [grant number EK158-03/10] for their financial assistance to analyse these specimens.

Notes on contributors

Jennifer R. Jones is currently a Teaching Fellow in Archaeological Science at the University of Aberdeen.

Jacqui A. Mulville is a Reader in Bioarchaeology, and Head of Archaeology and Conservation at Cardiff University.

ORCID

Jennifer R. Jones  <http://orcid.org/0000-0002-9247-7994>

Jacqui A. Mulville  <http://orcid.org/0000-0002-9392-3693>

References

- Amorosi, T., P. C. Buckland, K. J. Edwards, I. Mainland, T. H. McGovern, J. Sadler, and P. Skidmore. 1998. "They Did Not Live by Grass Alone: The Politics and Palaeoecology of Animal Fodder in the North Atlantic Region." *Environmental Archaeology* 1: 41–54.
- Ascough, P. L., M. J. Church, G. T. Cook, Á Einarsson, T. H. McGovern, A. J. Dugmore, and K. J. Edwards. 2014. "Stable Isotopic ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) Characterization of key Faunal Resources. From Norse Period Settlements in North Iceland." *Journal of the Northern Atlantic* 7 (7): 25–42.
- Balasse, M., I. Mainland, and M. P. Richards. 2009. "Stable Isotope Evidence for Seasonal Consumption of Marine Seaweed by Modern and Archaeological Sheep in the Orkney Archipelago (Scotland)." *Environmental Archaeology* 14: 1–14.
- Balasse, M., A. Tresset, and S. H. Ambrose. 2006. "Stable Isotope Evidence (d^{13}C , d^{18}O) for Winter Feeding on Seaweed by Neolithic Sheep of Scotland." *Journal of Zoology* 270: 170–176.
- Barrett, J. H. 1995. "'Few Know an Earl in Fishing Clothes': Fish Middens and the Economy of the Viking Age and Late Norse Earldoms of Orkney and Caithness, Northern Scotland." Unpublished PhD thesis, University of Glasgow.
- Barrett, J. H. 1997. "Fish trade in Norse Orkney and Caithness: a zooarchaeological approach." *Antiquity* 71 (273): 616–638.
- Barrett, J. H. 2012. *Being an Islander. Production and Identity at Quoygrew, Orkney AD900–1600*. Cambridge: McDonald Institute Monographs.
- Barrett, J. H., R. P. Beukens, and R. A. Nicholson. 2001. "Diet and Ethnicity During the Viking Colonization of Northern Scotland: Evidence From Fish Bones and Stable Carbon Isotopes." *Antiquity* 75: 145–154.
- Barrett, J., R. Beukens, I. Simpson, P. Ashmore, S. Poaps, and J. Huntley. 2000. "What Was the Viking Age and When did it Happen? A View From Orkney." *Norwegian Archaeological Review* 33: 1–40.
- Barrett, J. H., A. M. Locker, and C. M. Roberts. 2004. "Dark Age Economics' Revisited: the English Fish Bone Evidence AD 600–1600." *Antiquity* 78 (301): 618–636.
- Barrett, J., R. A. Nicholson, and R. Cerón-Carrasco. 1999. "Archaeo-ichthyological Evidence for Long-Term Socioeconomic Trends in Northern Scotland: 3500 BC to AD 1500." *Journal of Archaeological Science* 26: 353–388.
- Barrett, J. H., and M. P. Richards. 2004. "Identity, Gender, Religion and Economy: New Isotope and Radiocarbon Evidence for Marine Resource Intensification in Early Historic Orkney, Scotland, UK." *European Journal of Archaeology* 7: 249–271.
- Batey, C. E. 2003. "Excavations at the 'Earl's Bu, Orphir, Orkney, c1859–1939." *New Orkney Antiquaries Journal* 3: 29–71.
- Bond, J. M. 2007a. "The Mammal Bone." In *Investigations in Sanday, Orkney Volume 1: Excavations at Pool, Sanday, a Multi-Period Settlement*, edited by J. Hunter, J. M. Bond, and A. N. Smith, 207–262. Kirkwall: The Orcadian in association with Historic Scotland.
- Bond, J. M. 2007b. "The Bioarchaeological Evidence." In *The Excavations at Pool Sanday*, edited by J. Hunter, 169–286. Kirkwall: The Orcadian.
- Bond, J. M., and J. R. Hunter. 1987. "Flax-growing in Orkney From the Norse Period to the 18th Century." *Proceedings of the Society of Antiquaries Scotland* 117: 175–181.
- Britton, K., G. Müldner, and M. Bell. 2008. "Stable Isotope Evidence for Salt-Marsh Grazing in the Bronze Age Severn Estuary, UK: Implications for Palaeodietary Analysis at Coastal Sites." *Journal of Archaeological Science* 35: 2111–2118.
- Bullock, D. J. 1985. "Annual Diets of Hill Sheep and Feral Goats in Southern Scotland." *The Journal of Applied Ecology* 22: 423–433.
- Chisholm, B. S., D. E. Nelson, and H. P. Schwarcz. 1982. "Stable Carbon Isotope Ratios as a Measure of Marine Versus Terrestrial Protein in Ancient Diets." *Science* 216: 1131–1132.
- Colley, S. M. 1983. "The Role of Fish Bone Studies in Economic Archaeology: with Special Reference to the Orkney Isles." *Unpublished PhD Thesis*, University of Southampton.
- Collins, M. J., and P. Galley. 1998. "Towards an Optimal Method of Archaeological Collagen Extraction: the Influence of pH and Grinding." *Ancient Biomolecules* 2: 209–222.
- Cramp, L. J., J. Jones, A. Sheridan, J. Smyth, H. Whelton, J. Mulville, N. Sharples, and R. P. Evershed. 2014. "Immediate Replacement of Fishing with Dairying by the Earliest Farmers of the Northeast Atlantic Archipelagos." *Proceedings of the Royal Society B Biological Sciences* 281: 1–8.
- Crawford, B. 2013. *The Northern Earldoms: Orkney and Caithness From AD870 to 1470*. Edinburgh: John Donald.
- de la Vega-Leinert, A. C., D. E. Smith, and R. L. Jones. 2007. "Holocene Coastal Environmental Changes on the Periphery of an Area of Glacio-Isostatic Uplift: an Example From Scapa Bay, Orkney, UK." *Journal of Quaternary Science* 22 (8): 755–772.
- DeNiro, M. J. 1985. "Post-mortem Preservation and Alteration of in Vivo Bone Collagen Isotope Ratios in Relation to Paleodietary Reconstruction." *Nature* 317: 806–809.
- Dyer, C. 2002. *Making a Living in the Middle Ages*. London: Yale University Press.

- Grant, S. A., D. E. Suckling, H. K. Smith, L. Torvell, T. D. A. Forbes, and J. Hodgson. 1985. "Comparative Studies of Diet Selection by Sheep and Cattle: The Hill Grasslands." *The Journal of Ecology* 73: 987–1004.
- Guy, R. D., D. M. Reid, and H. R. Krouse. 1986a. "Factors Affecting 13C/12C Ratios of Inland Halophytes 1: Controlled Studies on Growth and Isotopic Composition of *Puccinellia Nuttalliana*." *Canadian Journal of Botany-Revue Canadienne de Botanique* 64: 2693–2699.
- Guy, R. D., D. M. Reid, and H. R. Krouse. 1986b. "Factors Affecting 13C/12C Ratios of Inland Halophytes 2: Ecophysiological Interpretations of Patterns in the Field." *Canadian Journal of Botany/Revue Canadienne de Botanique* 64: 2700–2707.
- Hamilton, J. R. C. 1956. *Excavations at Jarlshof, Shetland*. Edinburgh: HMSO.
- Hammer, Ø, D. A. T. Harper, and P. D. Ryan. 2001. "PAST: Paleontological Statistics Software Package for Education and Data Analysis." *Palaeontologia Electronica* 4 (1): 1–9.
- Hansom, D. 2005. "Archaeological Survivability and Past Coastal Processes." In *Coastal Archaeology and Erosion in Scotland*, edited by T. Dawson, 9–14. Edinburgh: Historic Scotland.
- Harland, J. F. 2006. "Zooarchaeology in the Viking Age to Medieval Northern Isles, Scotland: An Investigation of Spatial and Temporal Patterning." *Unpublished PhD Thesis*, University of York.
- Hoffmann, R. C. 1996. "Economic Development and Aquatic Ecosystems in Medieval Europe." *The American Historical Review* 101: 631–669.
- Hofmann, R. R. 1989. "Evolutionary Steps of Ecophysiological Adaptation and Diversification of Ruminants: a Comparative View of Their Digestive System." *Oecologia* 78: 443–457.
- Holm, S. 1979. "A Simple Sequential Rejective Multiple Test Procedure." *Scandinavian Journal of Statistics* 6: 65–70.
- Ingre, C. 2005. "The Fish Bones." In *A Norse Farmstead in the Outer Hebrides. Excavations at Mound 3 Bornais, South Uist*, *Cardiff Studies in Archaeology*, edited by N. Sharples. Oxford: Oxbow.
- Jones, J. R., and J. Mulville. 2016. "Isotopic and Zooarchaeological Approaches Towards Understanding Aquatic Resource use in Human Economies and Animal Management in the Prehistoric Scottish North Atlantic Islands." *Journal of Archaeological Science: Reports* 6: 665–677.
- Jones, J. R., J. A. Mulville, R. A. R. McGill, and R. P. Evershed. 2012. "Palaeoenvironmental Modelling of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ Values in the North Atlantic Islands: Understanding Past Marine Resource use." *Rapid Communications in Mass Spectrometry* 26: 2399–2406.
- Koshiba, S. B., R. H. Tykot, and D. Carlsson. 2007. "Stable Isotopes as Indicators of Change in the Food Procurement and Food Preference of Viking Age and Early Christian Populations on Gotland (Sweden)." *Journal of Anthropological Archaeology* 26 (3): 394–411.
- Longin, R. 1971. "New Method of Collagen Extraction for Radiocarbon Dating." *Nature* 230: 241–242.
- Lucas, G. M., and T. McGovern. 2007. "Bloody Slaughter: Ritual Decapitation and Display at the Viking Settlement of Hofstadir, Iceland." *European Journal of Archaeology* 10: 7–30.
- Madgwick, R., J. Mulville, R. Stevens, and T. C. O'Connell. 2012a. "The Machair 4: Isotopic Analysis of Fauna." In *A Late Iron Age Settlement in the Outer Hebrides: Excavations at Mound 1, Bornais, South Uist*, edited by N. Sharples, 243–246. Oxford: Oxbow.
- Madgwick, R., J. Mulville, and R. E. Stevens. 2012b. "Isotopic Analysis of Fauna From British Middens of the Late Bronze Age: Evidence for Diversity in Foddering Strategy and Herd Management." *Environmental Archaeology* 17: 126–140.
- Mainland, I. 1995. *A Preliminary Discussion of the Animal Bone Assemblage From the 1979–1993 Excavations at the Earl's Bu, Orphir, Orkney*. Sheffield Environmental Facility Report, 1995.
- Mainland, I. 2006. "Pastures Lost? A Dental Microwear Study of Ovicaprine Diet and Management in Norse Greenland." *Journal of Archaeological Science* 33: 238–252.
- Mainland, I., C. Batey, D. Griffiths, and P. Ascough. 2015. "Herding Economies, Sustainability and Resilience in Viking and Norse Orkney." Paper Presented at the European Archaeology Association Conference, Glasgow, 2015.
- Mainland, I., J. Towers, V. Ewens, G. Davis, J. Montgomery, C. Batey, N. Card, and J. Downes. 2016. "Toiling with Teeth: An Integrated Dental Analysis of Sheep and Cattle Dentition in Iron Age and Viking–Late Norse Orkney." *Journal of Archaeological Science: Reports* 6: 837–855.
- McGovern, T. H., S. Perdikaris, I. Ascough, P. Ewens, V. Einarsson, E. Sidell, J. Hambrecht, R. Harrison, and . 2009. "Chapter 4 : The archaeofauna." In *Hofstadir: Excavations of a Viking Age Feasting Hall in North Eastern Iceland*. Vol. Institute of Archaeology Monograph Series., edited by G. Lucas, 168–252. Reykjavik: Institute of Archaeology Reykjavik.
- Müldner, G., K. Britton, and A. Evershed. 2014. "Inferring Animal Husbandry Strategies in Coastal Zones Through Stable Isotope Analysis: new Evidence From the Flemish Coastal Plain (Belgium, 1st–15th Century AD)." *Journal of Archaeological Science* 41: 322–332.
- Mulville, J. 2010. "Red Deer on Scottish Islands." In *Extinctions and Invasions: A Social History of British Fauna*, edited by T. O'Conner and N. Sykes, 43–50. Oxford: Oxbow.
- Mulville, J., J. Bond, and O. Craig. 2005. "The White Stuff: Milking in the North Atlantic." In *The Zooarchaeology of Fats, Oils, Milk and Dairying ICAZ/Oxbow Series of Conference Proceedings*, edited by J. Mulville and A. Outram, 167–183. Oxford: Oxbow Books.
- Mulville, J., R. Madgwick, R. Stevens, T. O'Connell, O. Craig, A. Powell, N. Sharples, and M. Parker Pearson. 2009. "Isotopic Analysis of Faunal Material From South Uist, Western Isles, Scotland." *Journal of the Northern Atlantic* 2: 51–59.
- Mulville, J. A., and A. Powell. 2012. "The Faunal Remains. Bornais." In *A Late Iron Age Settlement in the Outer Hebrides: Excavations at Mound 1, Bornais, South Uist*, edited by N. Sharples, 191–194. Oxbow: Oxford.
- Mulville, J. A., and A. Powell. Forthcoming. "The Faunal Remains." In *Bornais M2 and 2A. A Norse Farmstead in the Outer Hebrides*, edited by N. Sharples. Oxford: Oxbow Books.
- Nelson, D. E., J. Heinemeier, J. Möhl, and J. Arneborg. 2012. "Isotopic Analyses of the Domestic Animals of Norse Greenland." *Journal of the Northern Atlantic* 301: 77–92.
- Parker Pearson, Mike, Mark Brennan, Jacqui Mulville, and Helen Smith. 2018. *Cille Pheadair: A Norse Farmstead and Pictish Burial Cairn*. Sheffield Environmental and

- Archaeological Research Campaign in the Hebrides, Vol. 7. Oxford: Oxbow books.
- Perdikaris, S. 1999. "From Chiefly Provisioning to Commercial Fishery: Long-Term Economic Change in Arctic Norway." *World Archaeology* 30: 388–402.
- Richards, M. P., B. T. Fuller, and T. I. Molleson. 2006. "Stable Isotope Palaeodietary Study of Humans and Fauna From the Multi-Period (Iron Age, Viking and Later Medieval) Site of Newark Bay, Orkney." *Journal of Archaeological Science* 33: 122–131.
- Richards, M. P., and P. A. Mellars. 1998. "Stable Isotopes and the Seasonality of the Oronsay Middens." *Antiquity* 72: 178–184.
- Schoeninger, M. J., and M. J. De Niro. 1984. "Nitrogen and Carbon Isotopic Composition of Bone Collagen From Marine and Terrestrial Animals." *Geochimica et Cosmochimica Acta* 48: 625–639.
- Schoeninger, M. J., M. J. De Niro, and H. Tauber. 1983. "Stable Nitrogen Isotope Ratios of Bone Collagen Reflect Marine and Terrestrial Components of Prehistoric Human Diet." *Science* 220: 1381–1383.
- Schulting, R. J., and M. P. Richards. 2002. "The Wet, the Wild and the Domesticated: The Mesolithic Neolithic Transition on the West Coast of Scotland." *European Journal of Archaeology* 5: 147–189.
- Schulting, R. J., A. Sheridan, R. Crozier, and E. Murphy. 2010. "Revisiting Quanterness: New AMS Dates and Stable Isotope Data From an Orcadian Chamber Tomb." *Proceedings of the Society of Antiquaries of Scotland* 140: 1–50.
- Schurr, M. R. 1997. "Stable Nitrogen Isotopes as Evidence for the age of Weaning at the Angel Site: A Comparison of Isotopic and Demographic Measures of Weaning age." *Journal of Archaeological Science* 24: 919–927.
- Schurr, M. R. 1998. "Using Stable Nitrogen-Isotopes to Study Weaning Behavior in Past Populations." *World Archaeology* 30 (2): 327–342.
- Sharples, N. 2005. *A Norse Farmstead in the Outer Hebrides. Excavations at Mound 3 Bornais, South Uist, Cardiff Studies in Archaeology*. Oxford: Oxbow.
- Sharples, N. Forthcoming. *Bornais M2 and 2A. A Norse Farmstead in the Outer Hebrides*. Oxford: Oxbow Books.
- Silver, I. A. 1969. "The Ageing of Domestic Animals." In *Science in Archaeology*, edited by D. Brothwell, and E. S. Higgs, 283–302. London: Thames and Hudson.
- Smith, H. 2012. "An Ethnohistory of Hebridean Agriculture." In *From Machair to Mountains: Archaeological Survey and Excavation in South Uist*, edited by M. Parker Pearson, 379–400. Oxford: Oxbow.
- Summers, J., and J. Bond. 2012. "The Agricultural Economy of a Late Wheelhouse." In *A Late Iron Age Settlement in the Outer Hebrides: Excavations at Mound 1, Bornais, South Uist*, edited by N. Sharples, 339–340. Oxford: Oxbow.
- van Groenigen, J. W., and C. van Kessel. 2002. "Salinity-induced Patterns of Natural Abundance Carbon-13." *Soil Science Society of America Journal* 66: 489–498.
- van Klinken, G. J. 1999. "Bone Collagen Quality Indicators for Palaeodietary and Radiocarbon Measurements." *Journal of Archaeological Science* 26: 687–695.
- Van Soest, P. J. 1984. *Nutritional Ecology of the Ruminant*. New York: Cornell University Press.
- Woolf, A. 2007. *From Pictland to Alba: Scotland, AD 789 to 1070*. Edinburgh: Edinburgh University Press.
- Zori, D., J. Byock, E. Erlendsson, S. Martin, T. Wake, and K. J. Edwards. 2013. "Feasting in Viking Age Iceland: Sustaining a Chiefly Political Economy in a Marginal Environment." *Antiquity* 87: 150–165.