Isotopic Analysis of Faunal Material from South Uist, Western Isles, Scotland

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Abstract - This paper reports on the results from stable isotope analysis of faunal bone collagen from a number of Iron Age and later sites on the island of South Uist, in the Western Isles, Scotland. This preliminary investigation into the isotopic signatures of the fauna is part of a larger project to model the interaction between humans, animals, and the broader environment in the Western Isles. The results demonstrate that the island fauna data fall within the range of expected results for the UK, with the terrestrial herbivorous diets of cattle and sheep confirmed. The isotopic composition for pigs suggests that some of these animals had an omnivorous diet, whilst a single red deer value might be suggestive of the consumption of marine foods, such as by grazing on seaweed. However, further analysis is needed in order to verify this anomalous isotopic ratio.

Introduction

This paper presents results from a preliminary study into faunal isotopic signatures from Prehistoric and Norse sites on the island of South Uist in the Western Isles of Scotland. The principal aims of the investigation are to reconstruct changing foddering regimes for the primary domesticates and dietary strategies among red deer in this restricted marginal island environment. This study represents one line of evidence in a broader project to model the interaction between humans, animals, and the wider environment in the Western Isles (e.g., Smith and Mulville 2004) based on data from the numerous excavations undertaken by the Sheffield Environmental Archaeological Research Campaign in the Hebrides (SEARCH) and allied projects.

The ratio of the stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) in bone collagen provides an established method for reconstructing the protein part of the diet of past populations (Ambrose 1993, 2000; Katzenberg 2000; Sealy 2001). The $\delta^{13}C$ values give an indication of the proportional contribution of terrestrial and marine sources of dietary protein, whilst $\delta^{15}N$ values reflect trophic level. In environments that lack C_4 plants, such as temperate Europe, high $\delta^{13}C$ collagen values demonstrate a contribution of marine-derived protein to the diet (e.g., Barrett et al. 2001), whilst high $\delta^{15}N$ values are indicative of the consumption of products from higher in the food chain (e.g., meat, fish, or dairy protein) (Schoeninger et al. 1983).

The majority of previous archaeological isotopic studies have focused on reconstructing the diet of human populations, but recent research has recognised the importance of faunal isotopic composition in providing a baseline from which to interpret human collagen data (e.g., Hedges and Reynard 2007, Jay and Richards 2007, Kosiba et al. 2007, O'Connell and Kimball 2006, Privat et al. 2002, Richards et al. 2006). Climatic changes can affect fractionation within the carbon and nitrogen cycles and result in small-scale variation in isotope signatures (Drucker et al. 2003, Murphy and Bowman 2006, Richards and Hedges 2003, Stevens and Hedges 2004, Stevens et al. 2008, van Klinken et al. 1994), though more local environmental effects may also occur, such as elevated nitrogen isotope values from sea spray (Britton et al. 2008, Virginia and Delwiche 1982). Consequently, samples from a range of food species are critical for the interpretation of human isotopic signatures and for modelling the interactions between humans, animals, and the environment over time.

The technique also has the potential to inform on human-mediated changes in animal diet, such as changes in the exploited pasturage, manuring practices (Bogaard et al. 2007, Jay and Richards 2006), and fodder provision at a population and individual level (e.g., the use of seaweed as fodder; Balasse et al. 2005, 2006). The identification of alternative fodder resources are of particular relevance to insular archaeology where high levels of neonatal mortality in cattle have been attributed to the low availability of hay fodder (Mulville et al. 2005). The exploitation of a diverse range of terrestrial and abundant marine resources, both directly and indirectly (as evidenced by the zooarcheaological and palaeobotanical record; Smith and Mulville 2004) results in complex human-mediated ecosystems that are challenging to model. The wide chronological range and quality of the archaeological record in the Western Isles marks these sites out as an excellent choice for examining

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both cultural and environmental effects on stable isotope values.

For this study, isotopic analysis was carried out on a new sample of Late Iron Age specimens from the multi-period assemblage at Bornais (Sharples 2005), and these results are compared with existing faunal data from other sites on South Uist (Bronze Age Cladh Hallan [Parker Pearson et al. 2005, 2007] and the later Norse assemblage at Bornais). Research on the human remains from these sites is also in progress (e.g., Parker Pearson et al. 2005, 2007), but is not discussed here.

Background

The sites

The settlement at Bornais was established in the Late Iron Age with the construction of a wheelhouse, which burnt down and was re-built as a rectangular building (4th to 6th century AD). This was succeeded by a Pictish phase of occupation with the later construction of up to 20 buildings in the Norse period (10th to 14th century AD). Bornais represents one of the largest and most important Norse settlements in the North Atlantic (Sharples 2005). Cladh Hallan is an Early Bronze Age to Iron Age settlement lying about 5 km south of Bornais and consisting of a number of roundhouses in its later phases. The first of these roundhouses was built around 1300 BC, and this long-lived site was occupied until around 500 BC (Parker Pearson et al. 2005, 2007).

Methods

Data are presented here for 40 Late Iron Age faunal specimens from Bornais, analysed in 2007 at the McDonald Institute, Cambridge, UK by the authors. Also presented are additional results from Late Iron Age ($n = 14$) and Norse Bornais ($n = 21$) obtained from radiocarbon samples analysed at the Scottish Universities Environmental Centre (SUERC) or the Oxford Radiocarbon Accelerator Unit (ORAU) as part of the site-dating program. The Cladh Hallan values were obtained from a specific study of isotopic signatures at the site undertaken at Newcastle University.

The 2007 samples were selected on a number of criteria: to include a range of terrestrial species, to avoid duplication of results from any one individual, and to avoid age-related dietary changes. Samples from three domestic (cattle [*Bos Taurus*], sheep [*Ovis aries*], and pig [*Sus scrofa*]) and one wild species (red deer [*Cervus elaphus*]) were selected and, when possible, separate animals were identified (e.g., by repeatedly sampling the same part and side of a particular element). Aging information was utilized to ensure that juveniles below weaning age were omitted. Collagen from the 2007 material was extracted following a modified Longin method (Longin 1971). Faunal samples were selected for the radiocarbon-dating programs without particular regard to the avoidance of repeat samples of single individuals or juveniles.

For all of the samples, material was analysed using an automated elemental analyzer coupled in continuous-flow mode to an isotope-ratio-monitoring mass-spectrometer (in Cambridge, a Costech elemental analyser coupled to a Finnigan MAT253 mass spectrometer, and in Oxford/Newcastle, a Carlo Erba elemental analyzer coupled to a PDZ Europa Geo 20/20 mass spectrometer). Stable isotope concentrations are measured as the ratio of the heavier isotope to the lighter isotope relative to an internationally defined scale—VPDB for carbon, and AIR for nitrogen (Hoefs 1997). Isotopic results are reported as δ values ($\delta^{13}C$ and $\delta^{15}N$) in parts per 1000 or "per mil" (‰) values, where

$$\delta^{15}N_{AIR} = ([^{15/14}N_{sample} / {}^{15/14}N_{AIR}] - 1) \times 1000.$$

Based on replicate analyses of international and laboratory standards, measurement errors are less than ±0.2‰ for $\delta^{13}C$ and $\delta^{15}N$. The analytical errors on samples analysed at ORAU are larger, potentially as large as ±0.4‰ (Peter Ditchfield, Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford, UK, pers. comm.). No inter-laboratory repeat testing was undertaken, but all samples were measured relative to International Atomic Energy Agency standards, with the McDonald Institute and ORAU also measuring the samples relative to the same in-house standard. Thus, the results from different laboratories are thought to be comparable.

Results

The Western Isles

Faunal isotope data for the sites are presented in Table 1. The Bornais Late Iron Age samples all yielded collagen and had atomic C/N ratios of 3.2 to 3.3, well within the range deemed to be indicative of acceptable collagen preservation (Ambrose 1990).

The mean $\delta^{13}C$ results from the combined Western Isles sites for cattle (-21.4‰), sheep (-21.1‰), and red deer (-21.5‰) samples are typical for herbivores living in a temperate C_3 ecosystem such as Britain (Richards and van Klinken 1997, van Klinken et al. 2000), and do not indicate the consumption of significant amounts of marine dietary sources. The mean $\delta^{15}N$ values for the herbivorous species from the South Uist sites—cattle (4.8‰), sheep (4.6‰), and deer (4.4‰) values—are typical of those found elsewhere for UK herbivores during the Holocene. The pig values, based almost exclusively on Late Iron Age animals with only a single Norse individual, differ in $\delta^{15}N$ compared to those of the cattle and sheep, with average values of -20.4‰ ($\delta^{13}C$) and 7.1‰ ($\delta^{15}N$). There is a small

Table 1. Mean $\delta^{13}C$ and $\delta^{15}N$ values for different taxa from sites on South Uist, Scotland.

	$\delta^{13}C$	$\delta^{15}N$	Std dev $\delta^{13}C$	Std dev $\delta^{15}N$	*n*
Cladh Hallan Bronze Age					
Cattle	-21.7	5	0.5	0.6	12
Sheep	-20.1	5.9	0.4	0.6	2
Red Deer	-21.2	4.9	0.0	0.5	2
Bornais Late Iron Age					
Cattle	-21.1	4.3	0.4	0.5	15
Sheep	-21.3	4.4	0.3	0.6	12
Pig	-20.6	6.9	0.4	0.8	9
Red Deer	-21.7	4.4	0.4	0.7	18
Bornais Pictish/Norse					
Cattle	-21.4	5.1	0.5	1.6	16
Sheep	-21.2	4.6	0.6	1.2	3
Pig	-19.3	8.7	-	-	1
Red Deer	-19	4.1	-	-	1
Western Isles Combined					
Cattle	-21.4	4.8	0.5	1.2	43
Sheep	-21.1	4.6	0.5	1.3	17
Pig	-20.4	7.1	0.6	0.9	10
Red Deer	-21.5	4.4	0.7	0.7	21

trophic-level increase in faunal $\delta^{13}C$ (0 to 2‰) and $\delta^{15}N$ (3 to 5‰) values (e.g., Bocherens and Drucker 2003, Rau et al. 1983, Schoeninger 1985, Schoeninger and DeNiro 1984), and carnivores and omnivores have higher $\delta^{13}C$ and $\delta^{15}N$ values than herbivores (Roth and Hobson 2000). These increased values of $\delta^{13}C$ and $\delta^{15}N$ in pigs may result from variation in the isotopic signal of the plant foods consumed (e.g., seeds vs. forage), or some animal protein input, such as scraps of meat, fish, dairy protein, or excrement. The range of variation within species (cattle 2.0‰, sheep 1.8‰, pig 1.8‰, red deer 2.5‰) is similar to that seen at other archaeological sites with large suites of faunal analyses, e.g., Neolithic Hazleton (Hedges et al. 2008).

Chronological changes

The mean values for the individual species from Bronze Age Cladh Hallan and the various phases at Bornais can be compared across time, as presented in Table 1 and Figure 1, with individuals of different species plotted by site in Figure 2.

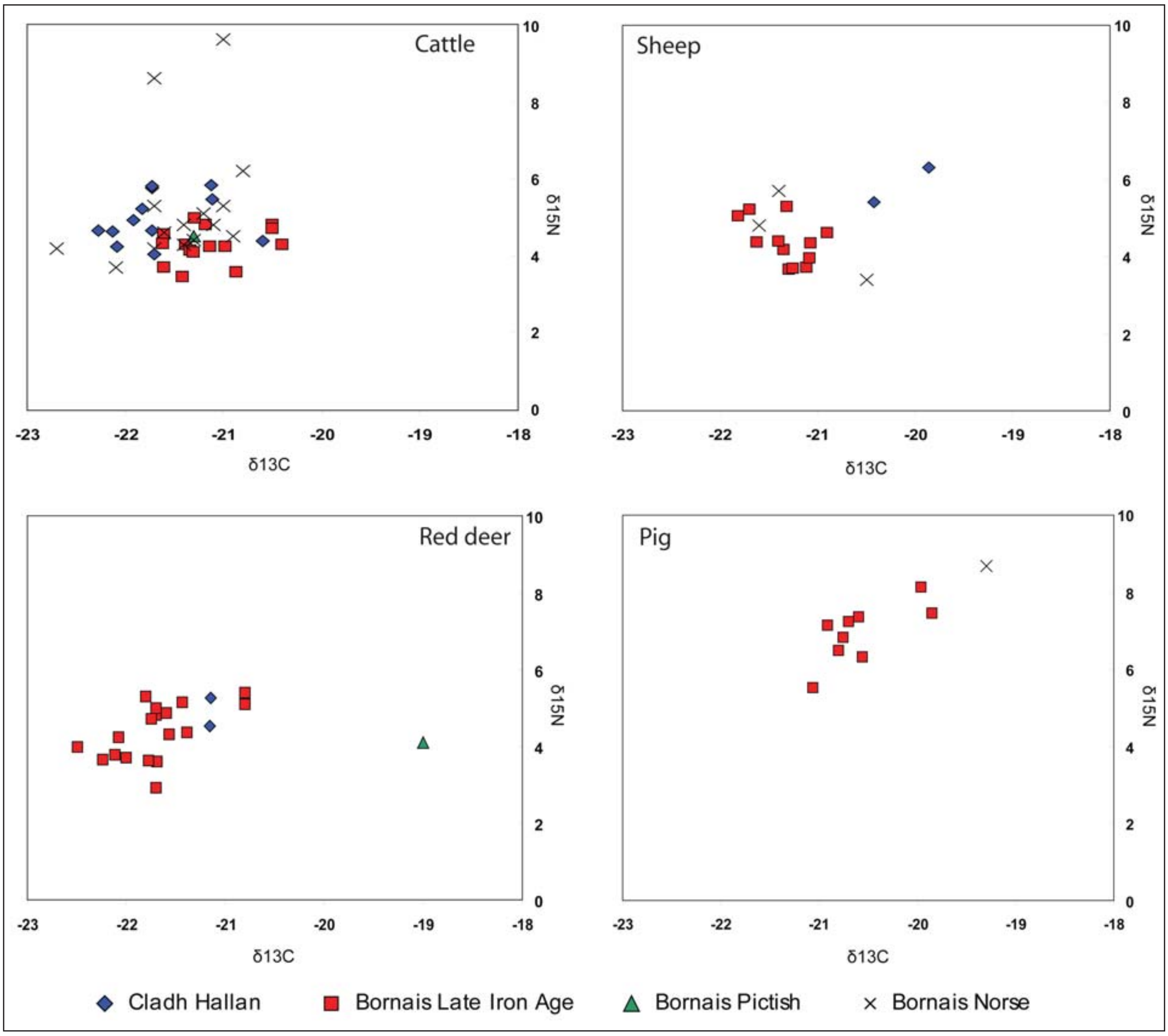

Figure 1. $\delta^{13}C$ and $\delta^{15}N$ values from cattle, sheep, pig, and red deer samples from South Uist, Scotland by site.

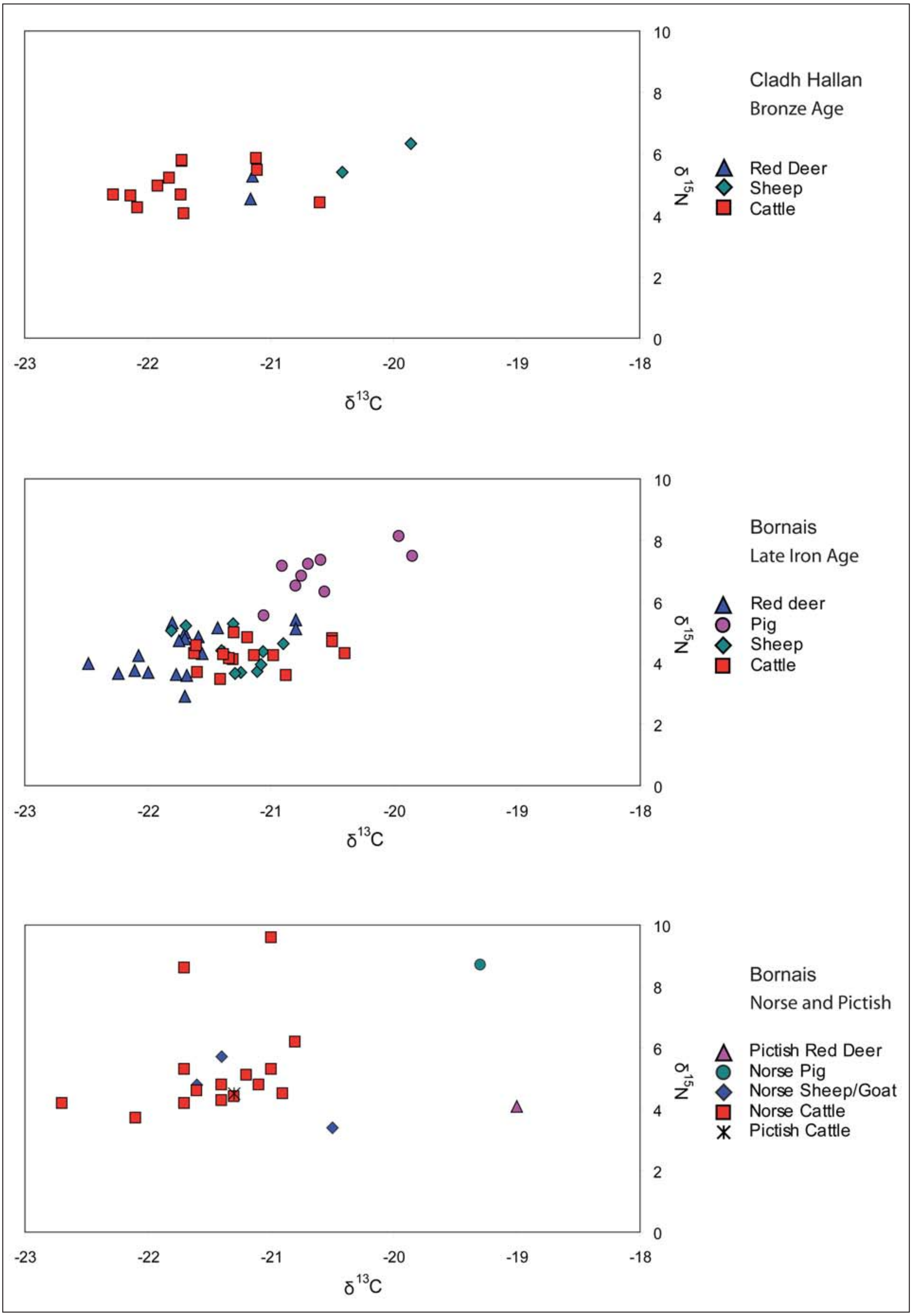

Figure 2. $\delta^{13}C$ and $\delta^{15}N$ values from cattle, sheep, pig, and red deer samples from South Uist, Scotland by species.

Cattle have similar $\delta^{13}C$ values (-20.5‰ to -22.5‰) through time, but vary slightly in $\delta^{15}N$, with the Iron Age values lower compared to the other two sites. There are two outliers with higher than expected $\delta^{15}N$ values (8.6‰ and 9.6‰) from the Norse period. These values were obtained from radiocarbon samples, and in the absence of detailed aging, may represent unweaned calves (Balasse and Tresset 2002, Hedges and Reynard 2007, Jenkins and Partridge 2001). A third outlying Norse cattle specimen has a low $\delta^{13}C$ level (-22.7‰).

The Bronze Age sheep at Cladh Hallan have slightly higher $\delta^{15}N$ and $\delta^{13}C$ values than the later sites. In such a small sample, the variation between these two sites is not substantial enough to be indicative of radically different feeding strategies or wider climatic changes. The few Norse sheep lie close to the range for Iron Age sheep.

Figure 2 demonstrates that the Bornais Iron Age pigs values, with averages of -20.6‰ ($\delta^{13}C$) and 6.9‰ ($\delta^{15}N$), differ markedly from cattle and sheep values, with the single Norse animal shifted even further along the $\delta^{13}C$ axis. This shift in $\delta^{13}C$ and $\delta^{15}N$ relative to the herbivorous cattle and sheep in the late Iron Age pig sample is indicative of a diet with an input from animal protein and possibly some marine foods. The Bronze Age and Norse datasets need considerable expansion before firm conclusions can be drawn on chronological shifts in pig diet.

With the exception of a single Pictish animal, all red deer specimens fall within the range of the domestic herbivore values. The Pictish red deer lies outside this range; its $\delta^{13}C$ value of -19‰ is higher than all of the pig specimens. In comparison, a study of 129 modern island British red deer indicated collagen $\delta^{13}C$ values ranging from -24.8‰ to -21.2‰ (Stevens et al. 2006), which is equivalent to -23.9‰ to -20.3‰ in archaeological populations accounting for fossil-fuel effects (Friedli et al. 1986). The elevated $\delta^{13}C$ of this single deer could be indicative of a marine element in feeding (Balasse et al. 2005, 2006). Modern red deer are known to graze upon seaweed (Fig. 3; Conradt 1999), which may explain the carbon shift in this archaeological specimen.

The wider archaeological context

Data for the main mammal groups from a range of Iron Age sites across Scotland (Lismore, Inner Hebrides [O'Connell and Kimball 2006]; and Port Seaton, Broxmouth, and Dryburn Bridge, East Lothian [Jay and Richards 2007]), the earlier Iron Age sites of England (Wetwang Slack, Yorkshire [Jay and Richards 2006]; Micheldever Wood and Winnall

Figure 3. Modern red deer stag grazing on seaweed on Rum (photograph © Deer Commission for Scotland).

Down, Hampshire; Harlyn Bay and Trevelgue Head, Cornwall [Richards and Jay 2007]; and Yarnton, Oxfordshire [Lightfoot et al., in press]) and the Norse site at Newark Bay, Orkney in the Northern Isles (Richards et al. 2006) are presented in Table 2.

The Western Isle cattle and sheep $\delta^{13}C$ and $\delta^{15}N$ values fall within the range found at the majority of comparative sites. The $\delta^{13}C$ values for herbivores (cattle, sheep, and red deer) range from -22.7 to -20.6‰, with the Lismore animals forming the bottom end of the range (-21.9 to -22.7‰) and occasional higher values scattered across the sites. The $\delta^{15}N$ values are more variable, with high sheep $\delta^{15}N$ values noted from Newark Bay, Broxmouth, and Yarnton, and with cattle values also elevated at the latter two. In a recent review of a number of these sites, this variation in nitrogen values has been attributed to variation in "baseline" environmental values (from the plants) at different locations (Jay and Richards 2007). At individual sites, this variation has been attributed to different management strategies, with animals grazing particular plants (e.g., salt-marsh vegetation; Britton et al. 2008) and/or a greater exposure to a sea-spray/salinity effect (Heaton 1987, Richards et al. 2006). The data reviewed in this paper does not support the existence of similar mechanisms for $\delta^{15}N$ enrichment at all coastal environments (contra Britton et al. 2008). Cattle and sheep values in the Western Isles and Cornwall, and cattle values in East Lothian are relatively low. Thus, high $\delta^{15}N$ values in the Bronze Age Seven Estuary (Britton et al. 2008) may be directly related to the specific salt-marsh vegetation in particular rather than to coastal vegetation in general.

Table 2. Mean $\delta^{13}C$ and $\delta^{15}N$ values for different faunal taxa at a selection of British Prehistoric sites.

Site	$\delta^{13}C$	$\delta^{15}N$	Std dev $\delta^{13}C$	Std dev $\delta^{15}N$	*n*
Inner Hebrides					
Lismore Iron Age					
Cattle	-22.4	4.6	0.5	0.6	5
Sheep/goat	-22.7	6.0	0.4	0.9	10
Pig	-21.9	6.0	0.7	0.8	4
Red deer	-22.1	4.0	0.5	0.1	2
Northern Isles					
Newark Bay Norse					
Cattle	-21.8	5.5	0.2	0.8	9
Sheep/goat	-21.8	7.0	0.8	0.9	5
Pig	-20.6	8.4	1.3	1.6	6
East Lothian					
Broxmouth Iron Age					
Cattle	-21.9	6.1	0.2	0.7	5
Sheep/goat	-21.6	6.4	0.2	0.8	7
Pig	-21.8	7.7	0.4	0.4	6
Red deer	-22.1	4.4	0.4	1.4	4
Dryburn Bridge Iron Age					
Cattle	-21.8	5.6	0.1	1.1	4
Sheep/goat	-21.8	6.3	-	-	1
Pig	-21.3	6.8	-	-	1
Port Seaton					
Cattle	-21.7	5.5	0.3	1.2	4
Sheep/goat	-21.8	7.4	0.3	0.4	3
Pig	-21.6	9.2	-	-	1
Yorkshire					
Wetwang Slack Iron Age					
Cattle	-21.5	4.6	0.5	1.1	10
Sheep/goat	-21.6	4.9	0.6	1.0	17
Pig	-21.6	6.4	0.6	1.5	11
Oxfordshire					
Yarnton Iron Age					
Cattle	-21.6	6.9	0.3	1.4	12
Sheep/Goat	-21.5	6.6	0.2	1.3	12
Pig	-21.7	8.1	0.4	0.8	12
Hampshire					
Micheldever Wood Iron Age					
Pig	-21.3	6.1	0.5	0.2	5
Winall Down					
Cattle	-21.8	4.5	0.4	1.1	11
Sheep/goat	-21.7	4.2	0.6	0.8	9
Pig	-21.4	5.7	0.6	1.0	4
Red deer	-21.9	5.2	-	-	1
Cornwall					
Halyn Bay Iron Age					
Cattle	-21.9	5.8	0.1	0.0	2
Pig	-22.4	5.7	-	-	1
Trevelgue Head					
Cattle	-22	4.8	0.3	2.0	7
Sheep/goat	-21.8	5.8	0.3	0.5	8
Pig	-21.5	7.1	0.4	1.4	8
Red deer	-22	5.4	0.2	0.5	4

The pig $\delta^{13}C$ values at the comparative sites are similar to those of the herbivores, but the range of $\delta^{15}N$ values are higher (5.7 to 9.2‰), suggestive of an omnivorous diet at some of the sites, as has been described for the Hebrides. This is not true of all sites, and at Lismore, in East Lothian, the similar $\delta^{13}C$ and $\delta^{15}N$ isotope values of the pig compared to sheep and/or cattle are indicative of an herbivorous diet. Red deer values are reported from four sites, all of which show lower average $\delta^{13}C$ values compared to sheep and cattle (-21.9 to -22.1‰) and a narrow range of $\delta^{15}N$ values (4 to 5.4‰) that lie within the range reported by Stevens et al. (2006). There is no evidence for higher carbon isotope values comparable to those reported from the Western Isles Norse deer and pig. This result highlights the unusual nature of these individual animal diets and that further research on the possible input of marine foods is required.

Discussion

These initial results have highlighted a number of points. Within the Western Isles, the representative nature of the dataset needs to be confirmed by enlarging the sample sizes to cover the full range of species across the chronological spread, to incorporate aging information into the datasets, and to avoid inter-laboratory biases. Data obtained from radiocarbon determinations have provided useful supplementary information, but slight measurement differences between laboratories could be significant in such small samples, especially when dealing with small isotopic shifts. The absence of pig and red deer data within the radiocarbon samples from Cladh Hallan and Norse Bornais, an indirect effect of the lower abundance of these species, hampered chronological comparisons.

The Western Isles results for domestic animals can be placed in context by comparison with wild species, as they are considered to provide a more accurate representation of isotopic signals in the wider environment. These species are free to make choices regarding their food input, and for the purpose of this study, red deer are assumed to reflect the stable isotope signal of freely grazing animals. The similarity in the level and low range of isotopic composition for the Western Isle deer and sheep suggests these animals have similar, herbivorous feeding patterns. However, there is a potential problem in using large wild herbivores to provide "natural" signals as their behaviour can be affected by humans—directly through hunting and indirectly through habitat destruction and disturbance which can promote changes in behaviour. This influence may be a particular problem in the Hebrides, where red deer play a large part in the food economy (Mulville, in press). In addition, the presence of anomalous values from a probable seaweed-eating deer highlights the variety that can be found with wild faunal diets. Future work on stable isotopes in the Western Isles will target additional wild species to establish background isotopic signals.

Interspecies comparisons within this Western Isles dataset demonstrate that the dietary signal for pigs is different to that of the herbivorous animals, with a distinctive animal protein input identified in the Late Iron Age Western Isles sample. The omnivorous nature of Late Iron Age pig diets in the Western Isles is consistent with the zooarchaeological models for their husbandry, with the low incidence of pig farming linked to the lack of available fodder and the potential for destruction of the plant cover by allowing these rooting animals to forage freely, exposing the light, unconsolidated soils to the strong winds characteristic of the Hebrides (Serjeantson 1990). The occasional pig is thought to have been reared by providing animal and plant food sources which would include scraps of meat, fish, and dairy waste along with excrement from humans and animals (Mulville 2005, Serjeantson 1990). The stable isotope data seem to confirm this model of small-scale intensive pig husbandry.

Overall, the results from the Western Isles lie within the range of other reported Iron Age and Norse sites (e.g., Jay and Richards 2007:187), despite their special status in terms of environment, marginality, and the extended duration of the Scottish Iron Age. There is a demonstrable degree of variation between the sites, particularly in nitrogen levels, which echoes comments made by Jay and Richards (2007), and suggests regional, chronological, and environmental variation. Further work is needed to elucidate the causes, particularly in relation to the effects of differing vegetation and exposure to sea spray. This study further reinforces the necessity for a good faunal baseline against which to measure all interpretations of human diet from carbon and nitrogen isotopic compositions for each individual locale (Jay and Richards 2007).

Conclusion

There are apparent isotopic differences between the Western Isle datasets, between the Scottish island sites, and also between the island and mainland sites, but these differences seem unrelated to larger environmental factors. However, although these results provide potential indications of both inter- and intra-taxon variation in feeding patterns, sample sizes are at present too small for confident interpretations to be made, as these limited datasets may contain individuals that are outliers to the general population. In addition, temporal climatic changes that impact on isotopic composition could be responsible for the inter-site variation on the islands, and it remains difficult to observe temporal diversification in animal management strategies. These results have been successful in picking up inter-species differences, which can be integrated with zooarchaeological analyses. There is a diversification of pig dietary foods not found elsewhere, although evidence for the use of marine foods as an additional source of fodder for domestic cattle has not been proven.

The range of faunal values demonstrated within and between the data sets continues to add to recent debates on the validity of isotopic models and the need for good faunal data upon which to base human dietary reconstructions and to better understand wider climatic shifts (Britton et al. 2008; Hedges and Reynard 2007; Jay and Richards 2007; Stevens et al. 2004, 2006). This study provides a starting point for a comprehensive program of isotopic analysis on larger samples from sites on the Western Isles and represents only an initial step in the large-scale isotopic modelling of a restricted island eco-system.

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Literature Cited

Ambrose, S.H. 1990. Preparation and characterization of bone and tooth collagen for isotopic analysis. Journal of Archaeological Science 18:293–317.

Ambrose, S.H. 1993. Isotopic analysis of paleodiets: Methodological and interpretive considerations. Pp. 59–130, *In* M.K. Sandford (Ed.). Investigation of Ancient Human Tissue: Chemical Analyses in Anthropology. Gordon and Breach Science Publishers, Langhorne, PA, USA.

Ambrose, S.H. 2000. Controlled diet and climate experiments on nitrogen isotope ratios of rats. Pp. 243–259, *In* S.H. Ambrose, and M.A. Katzenberg (Eds.). Biogeochemical Approaches to Palaeodietary Analysis. Kluwer Academic/Plenum Publishers, New York, NY, USA.

Balasse, M., and A. Tresset. 2002. Early weaning of Neolithic domestic cattle (Bercy, France) revealed by intra-tooth variation in nitrogen isotope ratios. Journal of Archaeological Science 29:853–859.

Balasse, M., A. Tresset, K. Dobney, and S.H. Ambrose 2005. The use of isotope ratios to test for seaweed eating in sheep. Journal of Zoology 266:283–291.

Balasse, M., A. Tresset, and S.H. Ambrose 2006. Stable isotope evidence ($\delta^{13}C$, $\delta^{18}O$) for winter feeding on seaweed by Neolithic sheep of Scotland. Journal of Zoology 270:170–176.

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.

Bocherens, H., and D. Drucker. 2003. Trophic-level isotopic enrichment of carbon and nitrogen in bone collagen: Case studies from recent and ancient terrestrial ecosystems International Journal of Osteoarchaeology 13:46–53

Bogaard, A., T.H.E. Heaton, P. Poulton, and I. Merbach. 2007. The impact of manuring on nitrogen isotope ratios in cereals: Archaeological implications for reconstruction of diet and crop management practices. Journal of Archaeological Science 34:335–343.

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.

Conradt, L. 1999. Use of a seaweed habitat by red deer (*Cervus elaphus* L.). Journal of the Zoological Society of London 250:541–549.

Drucker, D.G., H. Bocherens, and D. Billiou. 2003. Evidence for shifting environmental conditions in Southwestern France from 33,000 to 15,000 years ago derived from carbon-13 and nitrogen-15 natural abundances in collagen of large herbivores. Earth and Planetary Science Letters 216:163–173.

Friedli, H., H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer. 1986. Ice-core record of the $^{13}C/^{12}C$ ratio of the atmospheric CO_2 in the past two centuries. Nature 324:237–238.

Heaton, T.H.E., 1987. $^{15}N/^{14}N$ ratios of nitrate and ammonium in rain at Pretoria, South Africa. Atmosperic Environment 21:843–852.

Hedges, R.E.M., and L.M. Reynard. 2007. Nitrogen isotopes and the trophic level of humans in archaeology. Journal of Archaeological Science 34:1240–1251.

Hedges, R.E.M., A. Saville, and T.C. O'Connell. 2008. Characterizing the diet of individuals at the Neolithic chambered tomb of Hazleton North, Gloucestershire, England, using stable isotopic analysis. Archaeometry 50:114–128

Hoefs, J. 1997. Stable Isotope Geochemistry. Springer Publishers, Berlin, Germany.

Jay, M., and M.P. Richards. 2006. Diet in the Iron Age cemetery population at Wetwang Slack, East Yorkshire, UK: Carbon and nitrogen stable isotope evidence. Journal of Archaeological Science 33:653–662.

Jay, M., and R. Richards. 2007. British Iron Age Diet: Stable Isotopes and Other Evidence. Proceedings of the Prehistoric Society 73:169–190.

Jenkins, S., and S. Partridge. 2001. Nitrogen and carbon isotope fractionation between mothers, neonates, and nursing offspring. Oecologia 129:336–341.

Katzenberg, M.A. 2000. Stable isotope analysis: A tool for studying past diet, demography, and life history. Pp. 305–327, *In* M.A. Katzenberg and S.R. Saunders (Eds.). Biological Anthropology of the Human Skeleton. Wiley-Liss Publishers, New York, NY, USA.

Kosiba, 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 26:394–411.

Longin, R. 1971. New method of collagen extraction for radiocarbon dating. Nature 230:241–242.

Lightfoot, E., T. O' Connell, R. Stevens, J. Hamilton, G. Hey, and R.E.M. Hedges. In press. An investigation into Iron Age diet at Yarnton, Oxfordshire, using stable carbon and nitrogen isotopes. Oxford Journal of Archaeology.

Mulville, J. 2005. Mammalian bone: Resource exploitation, site activities, and discussion. Pp. 165–168, *In* N. Sharples (Ed.). A Norse Farmstead in the Outer Hebrides. Excavations at Mound 3, Bornais, South Uist. Cardiff Studies in Archaeology. Oxbow Books, Oxford, UK.

Mulville, J. In press. Wild things? Red deer on Scottish islands. *In* T.P. O'Connor and N. Sykes (Eds.). Extinctions and Invasions: A Social History of British Fauna. Windgather Press, Oxford, UK.

Mulville, J., J. Bond, and O. Craig. 2005. The white stuff: Milking in the North Atlantic. Pp. 167–183, *In* J. Mulville and A. Outram (Eds.). The Zooarchaeology of Fats, Oils, Milk, and Dairying. ICAZ/Oxbow series of conference proceedings. Oxbow Books, Oxford, UK.

Murphy, B.P., and D.M.J.S. Bowman. 2006. Kangaroo metabolism does not cause the relationship between bone collagen delta N-15 and water availability. Functional Ecology 20:1062–1069.

O'Connell T.C., and L.M. Kimball. 2006. Stable carbon and nitrogen isotope analysis of faunal remains from the Lismore Landscape Project: A preliminary report. Unpublished report for Historic Scotland, McDonald Institute for Archaeological Research, Cambridge University, Cambridge, UK.

Parker Pearson, M., A. Chamberlain, O.E. Craig, P. Marshall, J. Mulville, H. Smith, C. Chenery, M. Collins, G. Cook, G. Craig, J. Evans, J. Hiller, J. Montgomery, J. Schwenninger, G. Taylor, and T. Wess. 2005. Evidence for mummification in Bronze Age Britain. Antiquity 79:529–546.

Parker Pearson, M., A. Chamberlain, M. Collins, C. Cox, G. Craig, O.E. Craig, J. Hiller, P. Marshall, J. Mulville, and H. Smith. 2007. Further evidence for mummification in Bronze Age Britain. Antiquity 81(313) Project Gallery. Available online at www.antiquity.ac.uk/ProjGall/parker/index.html.

Privat, K.L., T.C. O'Connell, and M.P. Richards. 2002. Stable isotope analysis of human and faunal remains from the Anglo-Saxon cemetery at Berinsfield, Oxfordshire: Dietary and social implications. Journal of Archaeological Science 29:770–790.

Rau, G.H., A.F. Mearns, D.R. Young, R.J. Olson, H.A. Schafer, and I.R. Kaplan. 1983. Animal $^{13}C/^{12}C$ correlates with trophic level in pelagic food webs. Ecology 64:1314–1318.

Richards, M.P., and R.E.M. Hedges. 2003. Variations in bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of fauna from Northwest Europe over the last 40,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 193:261–267.

Richards, M.P., and G.J. van Klinken. 1997. A survey of European human bone stable carbon and nitrogen isotope values. Pp. 363–368, *In* A.G.M. Sinclair, E.A. Slater, and J.A.J. Gowlett (Eds.). Archaeological Sciences 1995. Oxbow Monograph 64. Oxbow Books, Oxford, UK.

Richards, M.P., B.T. Fuller, and T.I. Molleson. 2006. Stable isotope palaeodietary study of humans and faunal from the multi-period (Iron Age, Viking, and Late Medieval) site of Newark Bay, Orkney. Journal of Archaeological Science 33:122–131.

Roth, J.D., and K.A. Hobson. 2000. Stable carbon and nitrogen isotopic fractionation between diet and tissue of captive red fox: Implications for dietary reconstruction. Canadian Journal of Zoology 78:848–852.

Schoeninger, M.J., and M.J. DeNiro. 1984. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochimica et Cosmochimica Acta 48:625–639.

Schoeninger, M.J. 1985. Trophic-level effects on N/N and C/C ratios in bone collagen and strontium levels in bone mineral. Journal of Human Evolution 14:515–525.

Schoeninger, M.J., M.J. Deniro, and H. Tauber. 1983. Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. Science 220:1381–1383.

Sealy, J. 2001. Body tissue chemistry and palaeodiet. Pp. 269–279, *In* D.R. Brothwell and A.M Pollard (Eds.). Handbook of Archaeological Sciences. John Wiley and Sons Publishers, Chichester, UK.

Serjeantson, D. 1990. The introduction of mammals to the Outer Hebrides and the role of boats in stock management. Anthropozoologica 13:7–18.

Sharples, N. 2005. A Norse Farmstead in the Outer Hebrides. Excavations at Mound 3, Bornais, South Uist. Cardiff Studies in Archaeology. Oxbow Books, Oxford, UK.

Smith, H., and J. Mulville. 2004. Resource management in the Outer Hebrides: An assessment of the faunal and floral evidence from archaeological investigations. *In* R.A. Housely and G. Coles (Eds.). Atlantic Connections and Adaptations: Economies, Environments, and Subsistence in Lands Bordering the North Atlantic. Oxbow Books, Oxford, UK. AEA Symposia No. 21:48–64.

Stevens, R.E., A.M. Lister, and R.E.M. Hedges. 2006. Predicting diet, trophic level, and palaeoecology from bone stable isotope analysis: A comparative study of five red deer populations. Oecologia 149:12–21.

Stevens, R.E., and R.E.M. Hedges. 2004. Carbon and nitrogen stable isotope analysis of Northwest European horse bone and tooth collagen, 40,000 BP–present: Palaeoclimatic interpretations. Quaternary Science Reviews 23:977–991.

Stevens, R.E., R. Jacobi, M. Street, M. Germonpre, N.J. Conard, S.C. Munzel, and R.E.M. Hedges. 2008. Nitrogen isotope analyses of reindeer (*Rangifer tarandus*), 45,000 BP to 9,000 BP. Palaeoenvironmental Reconstructions 262(1–2):32–45.

van Klinken, G.J., J. van der Plicht, and R.E.M. Hedges. 1994. Bone $^{13}C/^{12}C$ ratios reflect (palaeo-) climatic variations. Geophysical Research Letters 21:445–448.

van Klinken, G.J., M.P. Richards, and R.E.M. Hedges. 2000. An overview of causes for stable isotopic variations in past European human populations: Environmental, ecophysiological, and cultural effects. Pp. 39–63, *In* S. Ambrose, and A. Katzenberg (Eds.). Biogeochemical Approaches to Palaeodietary Analysis. Kluwer Academic/Plenum publishers, New York, NY, USA.

Virginia, R.A., and C.C. Delwiche. 1982. Natural ^{15}N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. Oecologia 54:317–325.