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# Stable Isotopic (δ13C and δ15N) Characterization of Key Faunal Resources from Norse Period Settlements in North Iceland

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**Abstract** - During the Viking Age, Norse peoples established settlements across the North Atlantic, colonizing the pristine and near-pristine landscapes of the Faroe Islands, Iceland, Greenland, and the short-lived Vinland settlement in Newfoundland. Current North Atlantic archaeological research themes include efforts to understand human adaptation and impact in these environments. For example, early Icelandic settlements persisted despite substantial environmental impacts and climatic change, while the Greenlandic settlements were abandoned ca. AD 1450 in the face of similar environmental degradation. The Norse settlers utilized both imported domestic livestock and natural fauna, including wild birds and aquatic resources. The stable isotope ratios of carbon and nitrogen (expressed as δ13C and δ15N) in archaeofaunal bones provide a powerful tool for the reconstruction of Norse economy and diet. Here we assess the δ13C and δ15N values of faunal and floral samples from sites in North Iceland within the context of Norse economic strategies. These strategies had a dramatic effect upon the ecology and environment of the North Atlantic islands, with impacts enduring to the present day.

## Introduction

The Viking settlement of the North Atlantic commenced around AD 800, and was characterized by rapid expansion of the Norse over a wide geographical area, including Scotland, the Faroe Islands, Iceland, and Greenland (e.g., Arge et al. 2005, Dugmore et al. 2005, Sharples and Parker Pearson 1999, Vésteinsson et al. 2002). In a relatively short time, settlements were established in a broad set of ecological and climatic zones, and agriculture was established in many previously pristine environments (Dugmore et al. 2005, McGovern et al. 2007, Vésteinsson 1998). Macro-scale settlement outcomes varied markedly, from long-term sustainability in the Faroes and Iceland, to abandonment of Greenlandic settlements in the mid-15th century AD (Dugmore et al. 2007a, 2012). This variation is also evident on smaller geographical scales; in Iceland, the overall continuity of settlement is overlain by differences in the history and longevity of individual farm sites (Dugmore et al. 2007b). Understanding the mechanisms for this variation is a key component in the reconstruction of Viking histories in the North Atlantic, but this aim is frequently confounded by the complexity of social, economic, and environmental interactions that influenced the behavior of inhabitants at a site.

One recurring and crucial research question is: what economic strategy was in place at a particular settlement? Understanding economic practices, particularly in terms of diet and animal husbandry, is essential to the reconstruction of human–environment interactions. Over recent years, the utility of stable isotope analysis in this regard has become increasingly apparent (e.g., Ambrose 1986; Arneborg et al. 1999, 2012; Ascough et al. 2012; Barrett and Richards 2007; Richards and Hedges 1999; Richards et al. 2006; Schwarcz and Schoeninger 1991). In this study, we investigate the use of stable isotope ratios of carbon and nitrogen, expressed as δ13C and δ15N, as a tool to reconstruct economic practice at early Viking period sites within the region of Mývatnssveit, northern Iceland (Fig. 1).

Norse North Atlantic communities used both agricultural and wild resources to build a broad-spectrum, effective, and flexible subsistence system that was initially based on traditional economic knowledge from the Norse homelands and then adapted to local settings (Dugmore et al. 2005, 2012). The agricultural component involved cows, sheep, goats, pigs, horses, and dogs, plus, where possible, arable agriculture. The wild component varied but could include freshwater and marine fish, birds, and marine mammals. Individual farms generally operated as part of a multi-farm cooperative system, involving exchange of materials and products with communal management of practices, such as upland grazing. The economic system was not static, but instead

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responded to changing environmental conditions and social pressures.

Measurements of $\delta^{13}C$ and $\delta^{15}N$ are a valuable tool in archaeological palaeodietary reconstruction. These measurements represent an integration of $\delta^{13}C$ and $\delta^{15}N$ isotope values in food consumed over the time a tissue (e.g., bone collagen) was formed (Hedges et al. 2007, Hobson and Clark 1992, Tieszen 1978). There is also a diet-tissue offset, meaning that $\delta^{13}C$ and $\delta^{15}N$ increase within an organism with each trophic level up a food chain by typically ≈1–2‰ for $\delta^{13}C$ and 3–5‰ for $\delta^{15}N$. An increase in trophic level has also been observed in the $\delta^{15}N$ of neonatal and suckling animals relative to the tissues of the mother in both modern and archaeological populations (e.g., Ascough et al. 2012, Fuller et al. 2006). Although the typical source-consumer $\delta^{13}C$ offset is minimal, it should be noted that the bone collagen diet-tissue $\delta^{13}C$ offset appears to show species and diet-dependant variations (e.g., Hare et al. 1991), with a recent survey suggesting an offset of +3.6‰ for mammalian collagen (Szpak et al. 2012a). If the isotopic values of possible dietary components are sufficiently different, then the proportion of each component that was consumed by an organism can be assessed by analysis of its body tissues. $\delta^{13}C$ and $\delta^{15}N$ measurements of archaeological samples are usually made using bone collagen and have proved particularly useful in discriminating between terrestrial and marine components in the diet of human populations, as there is a large and consistent difference between both carbon and nitrogen isotope values in marine and terrestrial organisms (Arneborg et al. 1999, Richards et al. 2006, Sveinbjörnsdóttir et al. 2010). Commonly, this approach involves modelling the proportion of different theoretical dietary components. The accuracy of such isotope-based diet reconstruction depends heavily on how accurately the source isotopic compositions for each resource group represent the resources actually consumed. Thus, the selection of appropriate end-member values for such a model is critical (Dewar and Pfeiffer 2010). Importantly, both the resources included in the economic strategy of the inhabitants of the archaeological site and the isotope values of these resources must be known.

Values of $\delta^{13}C$ and $\delta^{15}N$ show wide geographical variation, meaning that the values for a species in one region cannot necessarily be used in palaeodietary reconstruction for another region. Geographic variations occur due to a range of environmental and anthropogenic variables, summarized in Rubenstein and Hobson (2004). Terrestrial $\delta^{13}C$ decreases with increasing latitude and increases with altitude due to temperature effects, while in $C_3$-plant-based ecosystems, dry habitats are enriched in $\delta^{13}C$ compared to wet habitats due to differences in water-use efficiency (Lajtha and Marshall 1994). In marine environments, $\delta^{13}C$ decreases with latitude, leading to northern oceans being enriched in $\delta^{13}C$ compared to southern oceans, and benthic systems are enriched in $\delta^{13}C$ compared to pelagic systems. These effects
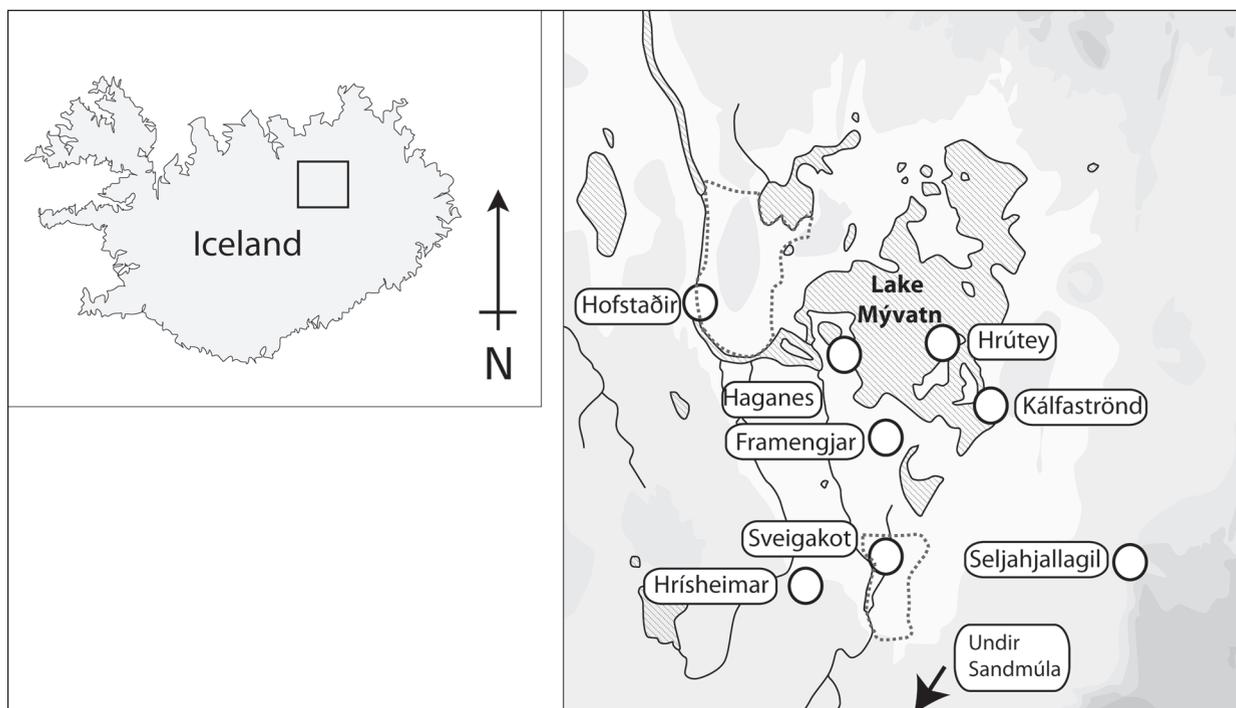


Figure 1. Location map of sites mentioned in the text

are ascribed to temperature differences, surface-water $CO_2$ concentration offsets, and differences in plankton biosynthesis or metabolism (Kelly 2000). Terrestrial plant tissue $\delta^{15}N$ varies according to the method of nitrogen fixation, the influence of anthropogenically and naturally added fertilizers, land-use practices resulting in differential loss of $^{14}N$, and the enrichment of wet habitats in $\delta^{15}N$ relative to dry habitats (Kelly 2000). Marine $\delta^{15}N$ geographic patterns are less well understood, although $\delta^{15}N$ in northern oceans appears more enriched compared to southern oceans (Kelly 2000). In addition to the above variables, the isotope values of any resource (e.g., cattle) at a single location will show considerable variability due to factors such as individual feeding preferences, age, sex, or illness (Bocherens and Drucker 2003, Hobson 1999, Hobson and Schwartz 1986).

This paper compiles stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values for a range of resources available to early Norse settlements in northern Iceland, within the region of Mývatnssveit, surrounding Lake Mývatn (Fig. 1, Table 1). These data include both domestic animals and wild resources from four archaeological sites: Undir Sandmúla (McGovern 2005), Sveigakot (Vésteinsson 2002), Hofstaðir (Lucas 2010), and Hrísheimar (Edvardsson and McGovern 2007). The region has been the focus of an international research effort to investigate human–environment interaction over the past twenty years (McGovern et al. 2007). The dataset presented here includes the first investigation of archaeological bird bone $\delta^{13}C$ and $\delta^{15}N$ for the study region. This inclusion is significant, given the extensive evidence for exploitation of bird populations surrounding Mývatn by the Norse inhabitants of Mývatnssveit (McGovern et al. 2007). In addition, analysis of bird remains from archaeological and paleontological contexts have contributed significantly to a better understanding of the ecology of a number of bird species (e.g., Chamberlain et al. 2005, Emslie and Patterson 2007, Fox-Dobbs et al. 2006), and so the results may have value beyond archaeological investigations.

The aim of the research is firstly to compile a new and more comprehensive assessment of the isotope values and their ranges for resources used in the Norse economy of the study area. Secondly, it aims to investigate the potential for using isotope analysis of archaeofaunal remains in informing researchers about animal husbandry practices in the study area. Animal husbandry is a key component within North Atlantic archaeology, but little research has addressed the direct reconstruction of animal diet through stable isotope analysis. This paper therefore assesses the isotopic values of archaeofauna from sites in Mývatnssveit (Table 1) to determine whether it is possible to use these data to detect differences in husbandry practices in differing environments and between sites of differing status or function. In omnivores, such as pigs, both $\delta^{13}C$ and $\delta^{15}N$ can vary significantly between animals obtaining nutrients through free-range pannage versus those that are stalled and fed upon domestic waste including animal protein. This difference is particularly evident if the domestic waste includes marine or freshwater resources. In herbivores, $\delta^{13}C$ values tend to show less variability in areas where plant communities are dominated by $C_3$ vegetation (as in Iceland). However, plant $\delta^{15}N$ values can vary widely, depending upon local environment. Of particular interest to the current study is that long-term intensive use of animal manure distinctly raises plant $\delta^{15}N$ values relative to unmanured areas (Bogaard et al. 2007; Bol et al. 2005; Commisso and Nelson 2006, 2007; Fraser et al. 2011; Kanstrup et al. 2011, 2012). This elevation is considerable and has been shown to be as high as 10‰ in cereal grains (Kanstrup et al. 2012). High $\delta^{15}N$ values in domestic animals may therefore indicate enhancement of production via manuring practices or feeding of stalled animals over winter. It is important to note that natural variation in plant $\delta^{15}N$ values can also be considerable, and baseline values are required. For this reason, the data presented here also include values of modern vegetation from zones unaffected by modern agriculture in Mývatnssveit.

## Methods

### Sample material

*Modern sample material.* Stable isotope values used in this study represent the $\delta^{13}C$ and $\delta^{15}N$ of

Table 1. Site descriptions from which material was obtained for analysis in this study.

| Site | Description |
|---|---|
| Mývatn | A highland lake basin in the interior of North Iceland |
| Haganes | Area adjacent to the Mývatn shoreline |
| Kálfaströnd | Area adjacent to the Mývatn shoreline |
| Seljahjallagil | Gorge located ~5 km south east of Mývatn |
| Framengjar | A large wetland area directly to the south of Mývatn |
| Hrúteyjarnes | An island within Mývatn |
| Undir Sandmúla | Archaeological site. Indeterminate-status Norse period farmstead |
| Sveigakot | Archaeological site. Low-status Norse period farmstead |
| Hofstaðir | Archaeological site. High-status Norse period farmstead |
| Hrísheimar | Archaeological site. Indeterminate-status Norse period farmstead |

both modern and archaeological biota from Mý-vatnssveit. These values include a range of new analyses and previously published measurements. Modern vegetation was obtained from four locations close to Mývatn (Haganes, Kálfaströnd, Framengjar, and Hrúteyjarnes) and from two locations ≈5 km from the lake in the vicinity of the archaeological site of Sveigakot (Sveigakot and Seljahjallagil; see Fig. 1). At Framengjar and Hrúteyjarnes, multiple vegetation samples were collected along a short transect to assess isotope variability in terrestrial plants at these locations in more detail. Leaves were sampled from living vegetation, air-dried at 30 °C, and then freeze-dried. Samples were stored in pre-cleaned glass vials or plastic bags prior to subsequent analysis. Living biota from within and around Mývatn, including freshwater fish, were obtained as described in Ascough et al. (2010). Wildfowl were procured from local gyrfalcon (*Falco rusticolus*) nests, or from gillnets in Lake Mývatn. Some were collected as roadkill adjacent to Mývatn as soon as practical after death. Full sample details are given in Table 2.

*Archaeofaunal sample material.* The dataset of Norse period archaeofauna included in this study were obtained from four sites of varying status in the Mývatnssveit region. Broadly, Hofstaðir is interpreted as a high-status farm, while specialist activities, such as industry, appear to have taken place at the farms of Hrísheimar and Undir Sandmúla. Finally, Sveigakot represents a lower-status farm site. The holdings at Hofstaðir, Hrísheimar, and Sveigakot are located at 250–350 m above sea level (asl), while the territory of Undir Sandmúla is located slightly higher, at ≈400 m asl. All samples retrieved date to the 9th to 11th centuries AD. The age of samples obtained was established through a combination of tephrochronology and radiocarbon ($^{14}$C) dating. Archaeofaunal samples included in the dataset are the bones of domesticated mammals (cow, sheep, goat, pig, horse, and dog) and wild species (birds and freshwater fish). These materials were obtained during excavations for two main projects: the Leverhulme Trust-funded "Landscapes circum-*landnám*" (Edwards et al. 2004) and the NSF-funded "Long Term Human Ecodynamics in the Norse North Atlantic: cases of sustainability, survival, and collapse" (McGovern 2011). Full sample details are given in Table 3.

**Laboratory methods**

Pretreatment of dried vegetation involved homogenization of each sample by grinding using an agate mortar and pestle. A sub-sample (≈2–3 mg) of the ground material was then taken for analysis.

Bone samples of modern organisms were de-fatted prior to collagen extraction with 2:1 (v/v) chloroform/methanol solution, followed by sonication for 60 minutes. The extraction was repeated until the solvent remained clear. Collagen was extracted from bone samples according to a modified Longin (1971) method. The sample surface was cleaned by abrasion with a Dremmel® tool, after which the bone was crushed and placed in 1M HCl at room temperature (≈20 °C). The bone was left in the HCl for up to 96 hours, after which dissolution of the bone mineral component was complete. The solution was then decanted, and the collagen washed in reverse-osmosis water. The collagen was placed in reverse-osmosis water and the solution pH adjusted to 3.0 by addition of 0.5 M HCl. The collagen was solubilized by gentle heating at ≈80 ºC. After cooling, the resulting solution was filtered through Whatman GF/A glass-fiber paper and then freeze-dried to recover the collagen. A sub-sample (≈0.5–1 mg) of the dried collagen was transferred into tin capsules for measurement of elemental abundance and stable isotope ratios.

Sample elemental abundances of %C and %N, to calculate CN ratios, were measured using a Costech elemental analyser (EA) (Milan, Italy) and fitted with a zero-blank auto-sampler. Vegetation samples were measured at the University of St. Andrews Facility for Earth and Environmental Analysis, and bone collagen samples were measured at the Scottish Universities Environmental Research Centre. The sample CN ratio was used to screen collagen samples for purity; samples with ratios of 2.9–3.6 were included in the dataset (cf. DeNiro 1985). Following combustion in the EA, the $\delta^{13}$C and $\delta^{15}$N of vegetation samples was measured using a ThermoFinnegan Delta$^{plus}$ XL, and the $\delta^{13}$C and $\delta^{15}$N of collagen was measured using a Thermo Fisher Scientific Delta V Advantage isotope ratio mass spectrometer (IRMS) (Thermo FisherScientific Inc. GmbH, Bremen, Germany). The EA and IRMS were linked via a ConFlo III (Werner et al. 1999). Isotope values thus obtained are reported as per mil (‰) deviations from the VPDB and AIR international standards for $\delta^{13}$C and $\delta^{15}$N. Samples were measured with a mix of appropriate laboratory standards and blanks, from which measurement precision (1σ) for $\delta^{13}$C was determined to be better than ± 0.2‰, and measurement precision (1σ) for $\delta^{15}$N was better than ± 0.3‰. Statistical differences in isotope values between archaeological sites for each archaeofaunal species were assessed using one-way analysis of variance (ANOVA) and post hoc Tukey tests.

Table 2. Stable isotope measurements of modern samples from Mývatnssveit. Previously published measurements: *Ascough et al. 2010, **Ascough et al. 2011. Modern terrestrial vegetation δ13C values are also given corrected for the Suess effect (i.e., -1.57‰; Feng and Epstein 1995, Keeling 1979, Keeling et al. 1979, McCarroll and Loader 2004, McCarroll et al. 2009).

| ID | Sample location | Latin name | Common name | Habitat; dietary preference | δ13C | Suess-corrected δ13C | δ15N | C/N |
|---|---|---|---|---|---|---|---|---|
| SUERC-19798* | Haganes | *Poa* sp. | Grass | Temperate grassland | -28.3 | -26.7 | 1.3 | 37 |
| SUERC-19799* | Kálfaströnd | *Poa* sp. | Grass | Temperate grassland | -29.1 | -27.5 | 2.6 | 23 |
| StA-1 | Sveigakot | *Poa* sp. | Grass | Temperate grassland | -28.2 | -26.6 | -6.3 | 33 |
| StA-2* | Seljahjallagil | *Poa* sp. | Grass | Temperate grassland | -28.5 | -26.9 | -9.1 | 25 |
| StA-3* | Seljahjallagil | *Equisetum arvense* | Field horsetail | Meadow | -26.9 | -25.3 | -2.6 | 19 |
| StA-4 | Kálfaströnd | *Equisetum arvense* | Field horsetail | Meadow | -29.2 | -27.6 | 1.4 | 17 |
| StA-5 | Framengjar | *Carex rostrata* | Bottle sedge | Wet meadows, Carr | -27.8 | -26.2 | -0.9 | 24 |
| StA-6 | Framengjar | *Vaccinium uliginosum* | Bog bilberry | Heaths, blanket bog | -30.1 | -28.5 | -5.5 | 29 |
| StA-7 | Framengjar | *Carex lyngbyei* | Lyngbye's sedge | Wetlands, brackish water | -27.8 | -26.2 | -0.9 | 26 |
| StA-8 | Framengjar | *Salix phylicifolia* | Tea-leaved willow | Damp/freshwater zones | -29.0 | -27.4 | -4.3 | 28 |
| StA-9 | Framengjar | *Betula nana* | Dwarf birch | Heaths, bogs | -29.4 | -27.8 | -4.9 | 22 |
| StA-10 | Framengjar | *Potentilla palustris* | Marsh cinquefoil | Marsh, stream/lake banks | -27.5 | -25.9 | 1.1 | 21 |
| StA-11 | Framengjar | *Salix lanata* | Woolly willow | Meadow, streamside | -28.4 | -26.8 | -4.1 | 26 |
| StA-12 | Framengjar | *Empetrum nigrum* | Crowberry | Heathland | -28.9 | -27.3 | -6.2 | 77 |
| StA-13 | Framengjar | *Bartsia alpina* | Alpine bartsia | Pastures and flushes | -29.4 | -27.8 | -3.6 | 25 |
| StA-14 | Framengjar | *Galium verum* | Lady's bedstraw | Meadows and pastures | -27.0 | -25.4 | -0.8 | 18 |
| StA-15 | Hrúteyjarnes | *Geranium* sp. | Geranium | Meadows, woodlands | -30.2 | -28.6 | 0.4 | 16 |
| StA-16 | Hrúteyjarnes | *Geum rivale* | Water avens | Wet meadow, bog, riparian zones | -29.0 | -27.4 | 1.7 | 19 |
| StA-17 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp/freshwater zones | -28.0 | -26.4 | 2.3 | 17 |
| StA-18 | Hrúteyjarnes | *Erysimum hieraciifolium* | Wallflower | Open damp grasslands | -30.6 | -29.0 | 1.8 | 9 |
| StA-19 | Hrúteyjarnes | *Angelica archangelica* | Angelica | Stream/lake shorelines | -30.9 | -29.3 | 2.1 | 11 |
| StA-20 | Hrúteyjarnes | *Geranium* sp. | Geranium | Meadows, woodlands | -28.8 | -27.2 | 4.0 | 12 |
| StA-21 | Hrúteyjarnes | *Geum rivale* | Water avens | Wet meadow, bog, riparian zones | -30.9 | -29.3 | 1.5 | 14 |
| StA-22 | Hrúteyjarnes | *Angelica archangelica* | Angelica | Stream/lake shorelines | -29.3 | -27.7 | 3.9 | 8 |
| StA-23 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -27.1 | -25.5 | 3.9 | 15 |
| StA-24 | Hrúteyjarnes | *Geum rivale* | Water avens | Wet meadow, bog, riparian zones | -31.6 | -30.0 | 1.9 | 16 |
| StA-25 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -29.1 | -27.5 | 3.4 | 18 |
| StA-26 | Hrúteyjarnes | *Geranium* sp. | Geranium | Meadows, woodlands | -26.9 | -25.3 | 2.1 | 14 |
| StA-27 | Hrúteyjarnes | *Angelica archangelica* | Angelica | Stream and lake shorelines | -29.5 | -27.9 | 3.7 | 12 |
| StA-28 | Hrúteyjarnes | *Geum rivale* | Water avens | Wet meadow, bog, riparian zones | -29.1 | -27.5 | 1.7 | 16 |
| StA-29 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -28.7 | -27.1 | 4.8 | 20 |
| StA-30 | Hrúteyjarnes | *Geranium* sp. | Geranium | Meadows, woodlands | -28.8 | -27.2 | 3.6 | 13 |
| StA-31 | Hrúteyjarnes | *Geum rivale* | Water avens | Wet meadow, bog, riparian zones | -30.9 | -29.3 | 2.6 | 16 |
| StA-32 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -30.5 | -28.9 | 5.0 | 16 |
| StA-33 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -30.5 | -28.9 | 6.5 | 17 |
| StA-34 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -30.8 | -29.2 | 4.1 | 17 |
| StA-35 | Hrúteyjarnes | *Salix phylicifolia* | Tea-leaved willow | Damp and freshwater zones | -31.3 | -29.7 | 4.6 | 17 |
| StA-36 | Hrúteyjarnes | *Geranium* sp. | Geranium | Meadows, woodlands | -30.6 | -29.0 | 3.0 | 12 |
| SUERC-19788* | Mývatn | *Salvelinus alpinus* | Arctic char | Fresh and/or marine waters; insectivore/piscivore | -14.0 | - | 5.8 | 7.0 |
| SUERC-19789* | Mývatn | *Gasterosteus aculeatus* | Three-spined stickleback | Fresh and/or marine waters; benthic insectivore | -13.4 | - | 5.4 | 4.6 |
| SUERC-19791* | Mývatn | *Tanytarsus gracilentus* | Chironomid midge | Freshwater | -14.4 | - | 0.5 | - |
| SUERC-19792* | Mývatn | *Tanytarsus gracilentus* | Chironomid larvae | Freshwater, benthic detritivore | -11.8 | - | -1.7 | - |
| SUERC-19793* | Mývatn | - | Bulk zooplankton | Freshwater pelagic; heterotrophic | -17.7 | - | 1.5 | - |
| SUERC-27076** | Mývatn | *Daphnia longispina* | Zooplankton | Freshwater pelagic ; algae and organic detritus | -17.0 | - | 1.2 | 7.2 |
| SUERC-27072** | Mývatn | *Apatania zonella* | Caddisfly larvae | Freshwater benthic; algae and detritus | -19.0 | - | -0.9 | 6.6 |
| SUERC-27062** | Mývatn | *Simulium vittatum* | Blackfly larvae | Freshwater, benthic detritivore | -15.4 | - | 1.2 | 5.1 |
| SUERC-27070** | Mývatn | *Tanytarsus gracilentus* | Chironomid larvae | Freshwater, benthic detritivore | -15.8 | - | 6.1 | 5.1 |
| SUERC-27071** | Mývatn | *Tanytarsus gracilentus* | Chironomid larvae | Freshwater, benthic detritivore | -19.3 | - | 0.7 | - |

P.L. Ascough, M.J. Church, G.T. Cook, Á. Einarsson, T.H. McGovern, A.J. Dugmore, and K.J. Edwards

Table 2, continued.

| ID | Sample location | Latin name | Common name | Habitat; dietary preference | δ¹³C | Suess-corrected δ¹³C | δ¹⁵N | C/N |
|---|---|---|---|---|---|---|---|---|
| SUERC-27068** | Mývatn | *Tanytarsus gracilentus* | Chironomid larvae | Freshwater, benthic detritivore | -16.1 | - | 0.4 | 5.2 |
| SUERC-27069** | Mývatn | *Tanytarsus gracilentus* | Chironomid larvae | Freshwater, benthic detritivore | -13.7 | - | 1.7 | 5.1 |
| SUERC-27082** | Mývatn | *Radix peregra* | Mollusc | Freshwater benthic; algae and detritus | -22.6 | - | 5.5 | 5.6 |
| SUERC-27086** | Mývatn | *Radix peregra* | Mollusc | Freshwater benthic; algae and detritus | -15.7 | - | 3.6 | 5.0 |
| SUERC-27081** | Mývatn | *Radix peregra* | Mollusc | Freshwater benthic; algae and detritus | -13.4 | - | 0.5 | 6.7 |
| SUERC-19797* | Mývatn | - | Detritus | Lake benthic detritus | -16.4 | - | -0.5 | - |
| SUERC-27059** | Mývatn | - | Detritus | Lake benthic detritus | -17. 5 | - | -1.9 | - |
| SUERC-27056** | Mývatn | - | Detritus | Lake benthic detritus | -18.3 | - | -0.4 | - |
| SUERC-27057** | Mývatn | - | Detritus | Lake benthic detritus | -17.7 | - | -3.1 | 6.6 |
| SUERC-27058** | Mývatn | - | Detritus | Lake benthic detritus | -16.5 | - | -2 | - |
| SUERC-27060** | Mývatn | - | Detritus | Lake benthic detritus | -19.2 | - | 6.3 | - |
| SUERC-27061** | Mývatn | - | Detritus | Lake benthic detritus | -17.4 | - | -2.1 | - |
| SUERC-27067** | Mývatn | *Cladophora* spp. | Green algae | Freshwater aquatic plant | -14.8 | - | -1.3 | 8.7 |
| SUERC-27066** | Mývatn | *Cladophora* spp. | Green algae | Freshwater aquatic plant | -10.1 | - | 3.4 | 16.7 |
| SUERC-19800* | Mývatn | *Myriophyllum alterniflorum* | Alternate water-milfoil | Freshwater aquatic plant | -10.2 | - | -1.3 | - |
| SUERC-19801* | Mývatn | *Potamogeton perfoliatus* | Perfoliate pondweed | Freshwater aquatic plant | -12.5 | - | 0.8 | - |
| SUERC-27079** | Mývatn | *Potamogeton filiformis* | Slender-leaved pondweed | Freshwater aquatic plant | -16.9 | - | 2 | 26.6 |
| SUERC-27080** | Mývatn | *Potamogeton filiformis* | Slender-leaved pondweed | Freshwater aquatic plant | -12.1 | - | -16 | 17.1 |
| SUERC-27077** | Mývatn | *Potamogeton filiformis* | Slender-leaved pondweed | Freshwater aquatic plant | -13.1 | - | -4.3 | 17.8 |
| SUERC-27078** | Mývatn | *Potamogeton filiformis* | Slender-leaved pondweed | Freshwater aquatic plant | -11.9 | - | -2.5 | 25.2 |
| StA-37 | Mývatn | *Melanitta nigra* | Common scoter | Inland/coastal waters; aquatic invertebrates, fish, vegetation | -7.9 | - | 5.4 | 3.4 |
| StA-38 | Mývatn | *Anas penelope* | Wigeon | Freshwater/coastal wetlands; herbivorous | -11.0 | - | 1.3 | 3.2 |
| StA-39 | Mývatn | *Numenius phaeopus* | Whimbrel | Freshwater/coastal wetlands; invertebrates, fish | -12.6 | - | 9.8 | 3.5 |
| StA-41 | Mývatn | *Sterna paradisaea* | Arctic tern | Coastal zone (may breed on inland water); piscivorous | -17.1 | - | 11.1 | 2.9 |
| StA-42 | Mývatn | *Podiceps auritus* | Slavonian grebe | Inland/coastal waters; fish and invertebrates | -10.6 | - | 8.0 | 3.2 |
| StA-44 | Mývatn | *Podiceps auritus* | Slavonian grebe | Inland/coastal waters; fish and invertebrates | -12.2 | - | 7.7 | 3.3 |
| StA-45 | Mývatn | *Podiceps auritus* | Slavonian grebe | Inland/coastal waters; fish and invertebrates | -13.1 | - | 10.5 | 3.1 |
| StA-46 | Mývatn | *Podiceps auritus* | Slavonian grebe | Inland/coastal waters; fish and invertebrates | -9.8 | - | 8.0 | 3.3 |
| StA-47 | Mývatn | *Aythya fuligula* | Tufted duck | Lakes, rivers, estuaries: Omnivorous | -23.2 | - | 16.4 | 3.5 |
| StA-49 | Mývatn | *Anas crecca* | Teal | Lake, marsh and river systems | -20.6 | - | 5.4 | 3.5 |
| StA-51 | Mývatn | *Bucephala islandica* | Barrow's goldeneye | Inland/coastal waters; aquatic insects, crustaceans and vegetation | -13.4 | - | 5.2 | 2.9 |
| StA-52 | Mývatn | *Podiceps auritus* | Slavonian grebe | Inland/coastal waters; fish and invertebrates | -14.6 | - | 10.4 | 3.0 |

Table 3. Stable isotope measurements of archaeological samples from Mývatnssveit. [†]Ascough et al. 2007, [*]Ascough et al. 2010, [§]Ascough et al. 2012. [x]Neonatal animal.

| Measurement ID | Sample location | Context No. | Latin name | Common name | $\delta^{13}C$ | $\delta^{15}N$ | C/N |
|---|---|---|---|---|---|---|---|
| StA-133 | Hofstaðir | 4 | Aythyinae | Diving duck | -12.6 | 6.1 | 3.0 |
| StA-134 | Hofstaðir | 8 | *Anas platyrhynchos* | Mallard | -11.9 | 5.1 | 3.3 |
| StA-135 | Hofstaðir | 4 | *Anas platyrhynchos* | Mallard | -11.6 | 7.0 | 2.9 |
| StA-136 | Hofstaðir | 1144 | Aythyinae | Diving duck | -9.7 | 5.8 | 3.0 |
| StA-138 | Hofstaðir | 6h | *Cepphus* sp. | Guillemot | -15.9 | 8.7 | 3.3 |
| StA-139 | Hofstaðir | 4a | Laridae (family) | Gull | -16.6 | 7.1 | 3.1 |
| StA-140 | Hofstaðir | 4a | *Lagopus* sp. | Ptarmigan | -20.0 | -4.9 | 3.4 |
| StA-141 | Hofstaðir | 4a | *Phalacrocorax carbo* | Cormorant | -12.0 | 5.4 | 3.3 |
| StA-142 | Hofstaðir | 5a | *Alle alle* | Little Auk | -21.0 | 5.2 | 2.9 |
| StA-143 | Hofstaðir | 16 | Aythyinae sp. | Diving duck | -15.0 | 13.9 | 2.9 |
| StA-144 | Hofstaðir | 4 | Aythyinae sp. | Diving duck | -13.1 | 4.8 | 2.9 |
| SUERC-3429[*][x] | Hofstaðir | 7a | *Bos taurus* | Cow | -21.0 | 5.9 | 3.1 |
| SUERC-3431[*][x] | Hofstaðir | 6d | *Bos taurus* | Cow | -20.3 | 1.6 | 3.1 |
| SUERC-3433[*] | Hofstaðir | 6g | *Bos taurus* | Cow | -20.9 | 3.8 | 3.3 |
| SUERC-6393[§] | Hofstaðir | 62 | *Bos taurus* | Cow | -21.2 | -0.1 | 3.2 |
| SUERC-6397[§] | Hofstaðir | 159 | *Bos taurus* | Cow | -21.3 | -0.1 | 3.2 |
| SUERC-6398[§] | Hofstaðir | 159 | *Bos taurus* | Cow | -21.4 | 0.6 | 3.1 |
| SUERC-6399[§] | Hofstaðir | 159 | *Bos taurus* | Cow | -21.4 | -0.2 | 3.2 |
| SUERC-8618[†] | Hofstaðir | 6N | *Bos taurus* | Cow | -21.2 | 1.4 | 3.2 |
| SUERC-8619[†][x] | Hofstaðir | 6N | *Bos taurus* | Cow | -21.0 | 2.6 | 3.3 |
| SUERC-8623[†] | Hofstaðir | 6N | *Bos taurus* | Cow | -21.2 | 0.1 | 3.1 |
| SUERC-8624[†] | Hofstaðir | 6N | *Bos taurus* | Cow | -21.4 | -0.2 | 3.3 |
| GU-14804[§] | Hofstaðir | 1495 | *Bos taurus* | Cow | -21.5 | 0.2 | 3.5 |
| SUERC-8353[§] | Hofstaðir | 233 | Ovicaprine | Sheep/Goat | -21.7 | 0.7 | 3.4 |
| SUERC-8354[§] | Hofstaðir | 254 | Ovicaprine | Sheep/Goat | -21.3 | 1.1 | 3.2 |
| SUERC-8360[§] | Hofstaðir | 170 | Ovicaprine | Sheep/Goat | -21.4 | 1.3 | 3.2 |
| SUERC-11541[§] | Hofstaðir | 760 | Ovicaprine | Sheep/Goat | -21.3 | 0.4 | 3.6 |
| SUERC-11547[§] | Hofstaðir | 170 | Ovicaprine | Sheep/Goat | -21.4 | 1.8 | 3.4 |
| GU-15267[§][x] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -21.3 | 4.0 | 3.1 |
| GU-15268[§][x] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -21.5 | 2.5 | 3.1 |
| GU-15269[§] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -21.0 | 0.5 | 3.1 |
| GU-15270[§] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -20.9 | 1.6 | 3.1 |
| GU-15271[§] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -20.8 | 1.2 | 3.1 |
| GU-15272[§] | Hofstaðir | 6M | Ovicaprine | Sheep/Goat | -21.0 | 0.2 | 3.1 |
| SUERC-8356[§] | Hofstaðir | 254 | *Ovis aries* | Sheep | -21.8 | 0.1 | 3.3 |
| SUERC-11542[§] | Hofstaðir | 4480 | *Ovis aries* | Sheep | -20.9 | 0.6 | 3.4 |
| SUERC-11546[§] | Hofstaðir | 1480 | *Ovis aries* | Sheep | -21.0 | 1.1 | 3.3 |
| GU-14805[§] | Hofstaðir | 1166 | *Ovis aries* | Sheep | -21.5 | 1.4 | 3.3 |
| SUERC-11540[*] | Hofstaðir | 219/470 | *Salmo trutta* | Brown trout | -12.2 | 6.8 | 3.5 |
| SUERC-11539[*] | Hofstaðir | 219/470 | *Salvelinus alpinus* | Arctic char | -12.5 | 5.7 | 3.4 |
| SUERC-3430[*] | Hofstaðir | 7a | *Sus scrofa* | Domestic pig | -21.0 | 4.6 | 3.4 |
| SUERC-3432[*] | Hofstaðir | 6d | *Sus scrofa* | Domestic pig | -21.5 | 0.5 | 3.5 |
| SUERC-3438[*] | Hofstaðir | 6g | *Sus scrofa* | Domestic pig | -19.8 | 3.7 | 3.2 |
| SUERC-8355[†] | Hofstaðir | 254 | *Sus scrofa* | Domestic pig | -16.9 | 7.4 | 3.2 |
| GU-15273[§][x] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -21.7 | 4.4 | 3.3 |
| GU-15274[§][x] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -21.2 | 0.9 | 3.3 |
| GU-15275[§] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -21.3 | 1.8 | 3.3 |
| GU-15276[§] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -18.9 | 6.6 | 3.4 |
| GU-15277[§] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -21.5 | 0.3 | 3.1 |
| GU-15278[§] | Hofstaðir | 6N | *Sus scrofa* | Domestic pig | -21.3 | 3.1 | 3.3 |
| StA-150 | Hrísheimar | 45 | *Anas crecca* | Teal | -23.6 | 3.6 | 3.4 |
| StA-154 | Hrísheimar | 384 | *Anser* sp. | Goose | -10.4 | 4.9 | 3.0 |
| SUERC-3445[§][x] | Hrísheimar | 60 | *Bos taurus* | Cow | -20.9 | 1.5 | 3.2 |
| SUERC-3446[*][x] | Hrísheimar | 2 | *Bos taurus* | Cow | -21.4 | 1.0 | 3.1 |
| SUERC-6431[†] | Hrísheimar | 45 | *Bos taurus* | Cow | -21.7 | -0.4 | 3.2 |
| SUERC-6432[†] | Hrísheimar | 45 | *Bos taurus* | Cow | -21.6 | 1.5 | 3.2 |
| SUERC-6433[†] | Hrísheimar | 45 | *Bos taurus* | Cow | -21.8 | 0.0 | 3.2 |
| SUERC-6437[†] | Hrísheimar | 45 | *Bos taurus* | Cow | -20.9 | 1.8 | 3.2 |
| GU-14807[§] | Hrísheimar | 429 | *Bos taurus* | Cow | -20.4 | 3.1 | 3.4 |
| GU-14808[§] | Hrísheimar | 429 | *Bos taurus* | Cow | -21.6 | 2.3 | 3.3 |
| GU-14809[§] | Hrísheimar | 429 | *Ovis aries* | Sheep | -21.0 | 1.6 | 3.4 |
| GU-15286[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.2 | -0.5 | 3.3 |

Table 3, continued.

| Measurement ID | Sample location | Context No. | Latin name | Common name | $\delta^{13}$C | $\delta^{15}$N | C/N |
|---|---|---|---|---|---|---|---|
| GU-15287[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.0 | 0.9 | 3.3 |
| GU-15288[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.3 | 0.6 | 3.4 |
| GU-15289[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.1 | 1.6 | 3.2 |
| GU-15290[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -22.0 | 1.7 | 3.6 |
| GU-15291[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.2 | -0.2 | 3.3 |
| GU-15292[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.2 | 0.6 | 3.2 |
| GU-15293[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.3 | -1.5 | 3.3 |
| GU-15294[§] | Hrísheimar | 3 | *Ovis aries* | Sheep | -21.6 | 0.3 | 3.4 |
| SUERC-9045[†] | Hrísheimar | 45 | *Salvelinus alpinus* | Arctic char | -15.9 | 6.0 | 3.1 |
| SUERC-9049[†] | Hrísheimar | 45 | *Salvelinus alpinus* | Arctic char | -16.0 | 5.7 | 3.3 |
| SUERC-9050[†] | Hrísheimar | 45 | *Salvelinus alpinus* | Arctic char | -15.5 | 5.6 | 3.2 |
| SUERC-9051[†] | Hrísheimar | 45 | *Salvelinus alpinus* | Arctic char | -15.9 | 5.8 | 3.2 |
| SUERC-3440[*] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -21.3 | 0.1 | 3.1 |
| SUERC-3442[*] | Hrísheimar | 2 | *Sus scrofa* | Domestic pig | -20.1 | 1.3 | 3.1 |
| GU-14806[§] | Hrísheimar | 429 | *Sus scrofa* | Domestic pig | -20.6 | 3.9 | 3.5 |
| GU-15279[§x] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -22.5 | -1.2 | 3.4 |
| GU-15280[§x] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -22.2 | -0.7 | 3.5 |
| GU-15281[§x] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -21.8 | 0.0 | 3.3 |
| GU-15282[§] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -22.2 | -0.4 | 3.5 |
| GU-15283[§] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -22.0 | -0.5 | 3.3 |
| GU-15284[§] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -21.3 | 0.1 | 3.2 |
| GU-15285[§] | Hrísheimar | 3 | *Sus scrofa* | Domestic pig | -21.9 | -0.6 | 3.3 |
| StA-155 | Sveigakot | 27 | Aythyinae | Diving duck | -20.5 | -2.7 | 2.9 |
| StA-156 | Sveigakot | 58 | *Gavia immer* | Great Northern diver | -14.5 | 14.2 | 3.4 |
| StA-158 | Sveigakot | 55 | *Podiceps auritus* | Slavonian grebe | -17.0 | 11.3 | 3.1 |
| StA-159 | Sveigakot | 4 | *Podiceps auritus* | Slavonian grebe | -11.9 | 11.1 | 3.0 |
| StA-160 | Sveigakot | 2 | *Anser* sp. | Goose | -13.5 | 14.1 | 2.9 |
| StA-161 | Sveigakot | 54 | Anatidae | Ducks, geese, swans (family) | -13.8 | 8.6 | 2.9 |
| StA-162 | Sveigakot | 2 | Aythyinae | Diving duck | -12.2 | 4.2 | 2.9 |
| StA-163 | Sveigakot | 1437 | Laridae (family) | Gull | -15.6 | 15.0 | 3.1 |
| StA-164 | Sveigakot | 55 | *Gavia stellata* | Red throated diver | -13.6 | 12.6 | 3.1 |
| GUsi-1312 | Sveigakot | 2859 | *Bos taurus* | Cow | -21.5 | 2.7 | 3.3 |
| GU-15461[§] | Sveigakot | 55 | *Bos taurus* | Cow | -21.5 | 1.2 | 3.2 |
| GU-15462[§] | Sveigakot | 55 | *Bos taurus* | Cow | -21.3 | 0.2 | 3.3 |
| GU-15463[§] | Sveigakot | 55 | *Bos taurus* | Cow | -22.1 | 0.3 | 3.3 |
| GU-15464[§] | Sveigakot | 55 | *Bos taurus* | Cow | -21.3 | 0.9 | 3.3 |
| GU-15465[§x] | Sveigakot | 55 | *Bos taurus* | Cow | -20.9 | 2.3 | 3.4 |
| GU-15466[§x] | Sveigakot | 55 | *Bos taurus* | Cow | -21.2 | 2.1 | 3.5 |
| GU-15467[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.1 | 0.0 | 3.3 |
| GU-15468[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.1 | -0.6 | 3.4 |
| GU-15469[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.1 | 0.3 | 3.3 |
| GU-15470[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.5 | 0.4 | 3.6 |
| GU-15471[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.3 | 0.0 | 3.3 |
| GU-15472[§] | Sveigakot | 55 | Ovicaprine | Sheep/Goat | -21.1 | -0.3 | 3.3 |
| GUsi-1316 | Sveigakot | 2859 | *Ovis aries* | Sheep | -21.8 | 0.5 | 3.4 |
| GUsi-1317 | Sveigakot | 2859 | *Ovis aries* | Sheep | -21.2 | 1.2 | 3.2 |
| GUsi-1318 | Sveigakot | 2859 | *Ovis aries* | Sheep | -21.9 | 1.4 | 3.6 |
| GUsi-1319 | Sveigakot | 2859 | *Ovis aries* | Sheep | -21.3 | 1.2 | 3.3 |
| GUsi-1314 | Sveigakot | 2859 | *Sus scrofa* | Domestic pig | -21.6 | 5.0 | 3.6 |
| GU-15473[§] | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -19.8 | 3.0 | 3.5 |
| GU-15474 | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -21.3 | 0.2 | 3.3 |
| GU-15475 | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -17.8 | 8.7 | 3.4 |
| GU-15476[x] | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -21.3 | 2.0 | 3.5 |
| GU-15477 | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -20.4 | 3.3 | 3.4 |
| GU-15478 | Sveigakot | 55 | *Sus scrofa* | Domestic pig | -21.5 | 3.0 | 3.3 |
| SUERC-11548 | Undir Sandmúla | 2 | *Bos taurus* | Cow | -21.6 | 2.1 | 3.4 |
| SUERC-11549 | Undir Sandmúla | 2 | *Bos taurus* | Cow | -21.6 | 0.1 | 3.6 |
| GU-14803[§] | Undir Sandmúla | 2 | *Capra hircus* | Goat | -21.4 | -1.0 | 3.3 |
| GU-14799[§] | Undir Sandmúla | 2 | Ovicaprine | Sheep/Goat | -21.3 | -1.3 | 3.3 |
| GU-14800[§] | Undir Sandmúla | 2 | Ovicaprine | Sheep/Goat | -21.4 | -0.2 | 3.5 |
| GU-14801[§] | Undir Sandmúla | 2 | Ovicaprine | Sheep/Goat | -21.3 | -0.8 | 3.5 |
| GU-14802[§] | Undir Sandmúla | 2 | Ovicaprine | Sheep/Goat | -21.5 | -1.0 | 3.6 |

## Results and Interpretations

### Modern vegetation and biota from Mývatnssveit

*Modern terrestrial vegetation*. The raw $\delta^{13}C$ values of modern terrestrial vegetation were adjusted by +1.57‰ (Feng and Epstein 1995, McCarroll and Loader 2004, McCarroll et al. 2009) to account for the decrease in atmospheric $\delta^{13}C$ since ca. AD 1880 due to human burning of fossil fuels (the Suess effect; Keeling 1979, Keeling et al. 1979)). The corrected $\delta^{13}C$ values ranged from -30.0 to -25.3‰, and the $\delta^{15}N$ values ranged from -9.0 to +6.5‰ (Table 2, Fig. 2). These values accord with previous measurements by Wang and Wooller (2006) and Gratton et al. (2008) of plant $\delta^{15}N$ values for a range of locations in Iceland. The $\delta^{13}C$ values of all sites falls within the same broad range. In contrast, the $\delta^{15}N$ values of samples from Haganes, Kálfaströnd, and Hrúteyjarnes (+0.4 to +6.5‰; average = +2.9‰) is higher than that of samples from Framengjar, Sveigakot, and Seljahjallagil (−9.0 to +1.1‰; average = -3.7‰). The sampling sites of Hrúteyjarnes and Framengjar in particular were selected due to the lack of modern grazing animals at these locations,

meaning that the elevated $\delta^{15}N$ values at Hrúteyjarnes are unlikely to be due to the effect of manuring via these species. An alternative explanation for higher plant $\delta^{15}N$ values at Haganes, Kálfaströnd, and Hrúteyjarnes is higher $\delta^{15}N$ of bioavailable soil nitrogen (as $NH_4^+$ or $NO_3^-$) at these sites. One potential source is the transportation of nitrogen from the lake to the shore in the bodies of chironomids (nonbiting midges). Gratton et al. (2008) estimated that, on average, 17 kg N $ha^{-1}$ $d^{-1}$ (kilograms of nitrogen per hectare, per day) were transported from Lake Mývatn to the terrestrial environment in this way, and that midge abundances decreased logarithmically with distance from shore. In contrast to our results, Gratton et al. (2008) did not find elevated $\delta^{15}N$ values in plants close to Mývatn. A further potential source of elevated plant $\delta^{15}N$ values close to the lake is that of guano from nesting bird populations. Bird guano has been shown to elevate plant $\delta^{15}N$ values considerably in experimental studies (Szpak et al. 2012b).

The results of stable isotope measurements on modern vegetation show that there is a wide range
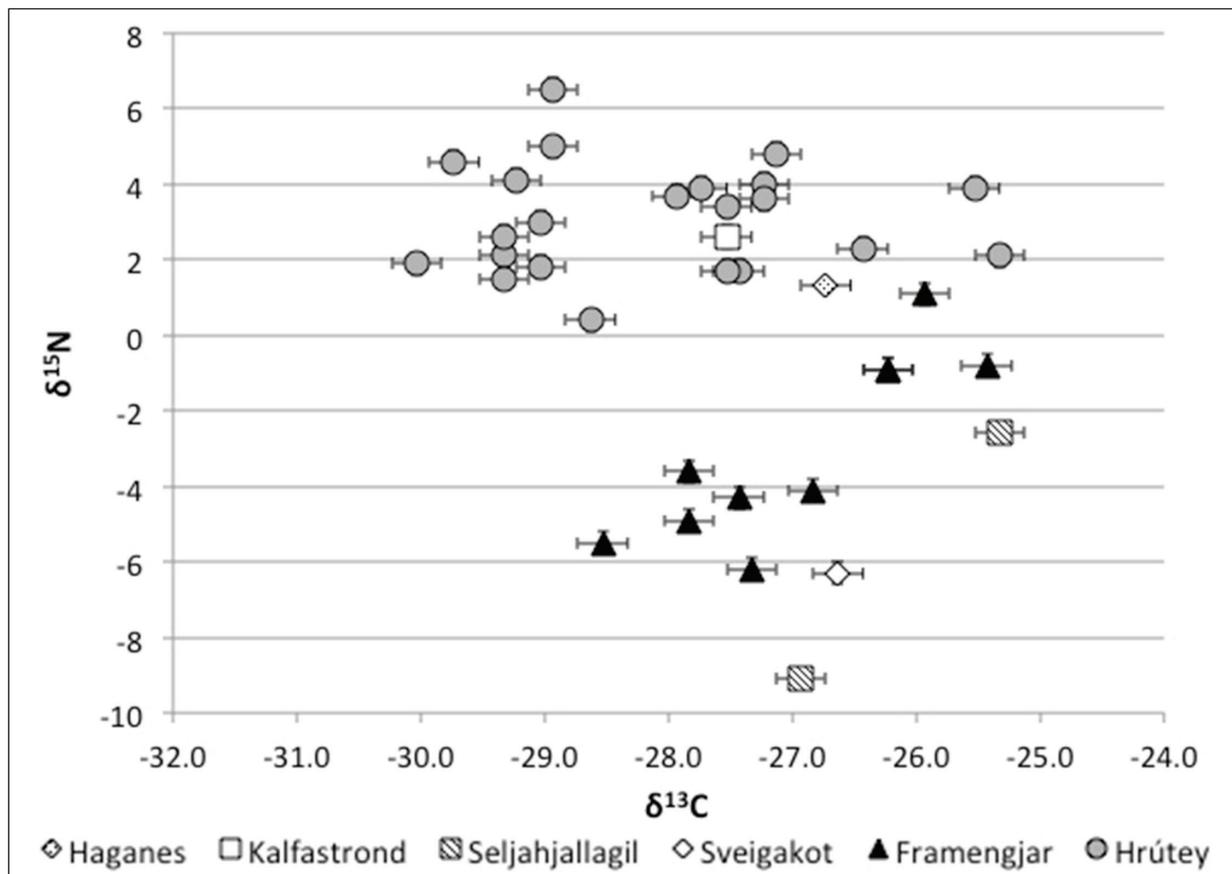


Figure 2. Modern vegetation samples from Mývatnssveit. Bars represent 1σ measurement precision (i.e., ± 0.2‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$). $\delta^{13}C$ values are given corrected for the Suess effect (i.e., -1.57‰; Feng and Epstein 1995, Keeling 1979, Keeling et al. 1979, McCarroll and Loader 2004, McCarroll et al. 2009).

in $\delta^{13}C$ and $\delta^{15}N$ values in plants in the Mývatn area. While $\delta^{13}C$ is variable at all sites, $\delta^{15}N$ values appear to differ significantly between locations. The expected $\delta^{15}N$ values of modern herbivores consuming plants exclusively from Framengjar, Sveigakot, and Seljahjallagil would therefore be ≈0–2‰, whereas the expected $\delta^{15}N$ values of animals consuming plants at Haganes, Kálfaströnd, and Hrúteyjarnes would be ≈6–8‰. These values are based on the average $\delta^{15}N$ value of plants at these locations, meaning that the actual range in animal $\delta^{15}N$ values at any location is likely to be larger than the values quoted above. Despite this, the overall $\delta^{15}N$ value of a population at Hrúteyjarnes, for example, would be expected to be higher than an equivalent population at Framengjar.

*Modern freshwater biota and birds.* The range in $\delta^{13}C$ and $\delta^{15}N$ values within modern freshwater biota in Mývatn, with respect to internal spatial lake variability, is discussed in detail in Ascough et al. (2011). However, the overall $\delta^{13}C$ and $\delta^{15}N$ values of lake biota also have relevance for the isotope values of wild resources (freshwater fish and birds) that were exploited by the Norse inhabitants of Mývatnssveit. The range in isotope values for individual species fits the established food web of Mývatn presented in Einarsson et al. 2004, where the trophic pathways from detritus up to waterfowl and fish are illustrated. The overall $\delta^{13}C$ value of modern freshwater biota is higher than that of terrestrial plants, meaning that the $\delta^{13}C$ values of fish and birds obtaining carbon from the lake will generally be higher than that of terrestrial herbivores (cf. Ascough et al. 2012). In contrast, the $\delta^{15}N$ values of aquatic plants and invertebrates are within the range of that represented in terrestrial vegetation samples. Excluding an extreme $\delta^{15}N$ value of -16‰ (discussed in Ascough et al. 2011), the $\delta^{15}N$ value range is -4.3 to +6.1‰. Thus, the $\delta^{15}N$ of organisms consuming freshwater resources will overlap with that of organisms consuming terrestrial plants in Mývatnssveit (Ascough et al. 2012). An important point concerning the $\delta^{13}C$ and $\delta^{15}N$ values of modern freshwater biota is that values for both these isotopes show large variability within the lake. This variation may therefore be reflected in the $\delta^{13}C$ and $\delta^{15}N$ values of organisms consuming lake biota.

The $\delta^{13}C$ values of modern bird bones from around Mývatn ranged from -23.2 to -7.9‰, and the $\delta^{15}N$ values for these samples ranged from +1.3 to +16.4‰ (Table 2, Fig. 3). The very wide range in these values reflects the broad diet of the sampled
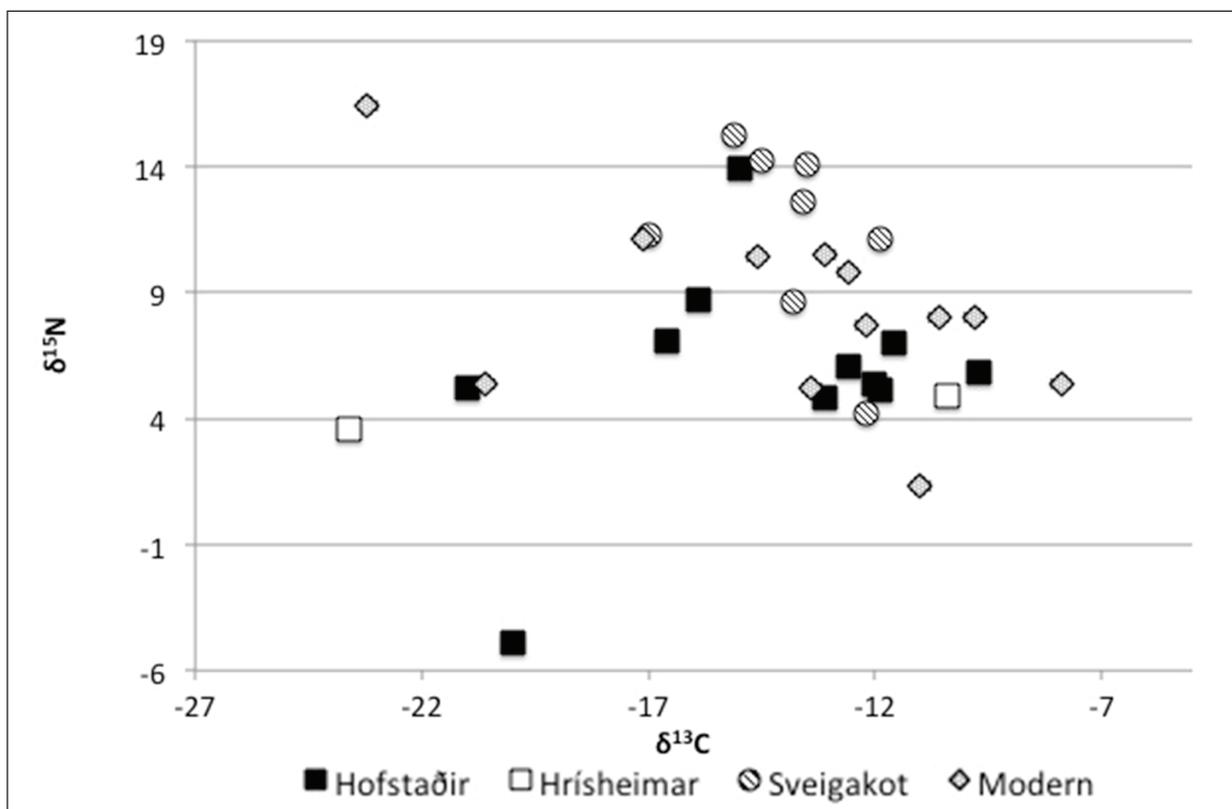


Figure 3. Modern and archaeofaunal bird bone collagen isotope values for archaeofaunal samples from Mývatnssveit. Bars represent 1σ measurement precision (i.e., ± 0.2‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$).

P.L. Ascough, M.J. Church, G.T. Cook, Á. Einarsson, T.H. McGovern, A.J. Dugmore, and K.J. Edwards

birds. While some species have a diet of terrestrial material (e.g., the whimbrel), the majority of other species incorporate freshwater and marine resources in their diets. The broad range in freshwater biota $\delta^{13}C$ and $\delta^{15}N$ values discussed above is hence represented in the $\delta^{13}C$ and $\delta^{15}N$ values of bird tissues. In addition, some birds represented in the sample group are piscivorous (Slavonian grebe), and hence will be at higher trophic levels than other species. In addition, most are migratory, spending part of the year in marine environments. This life history means that the $\delta^{13}C$ and $\delta^{15}N$ values of their tissues represent an integration of many different dietary resources from a variety of locations. One important point here regards differences in tissue turnover rates; the isotopic values of tissues with rapid turnover (e.g., muscle) reflect recent diet, whereas tissues with slower turnover (e.g., bone collagen) reflect longer-term dietary averages (Hobson and Clark 1992). Therefore, the bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of migratory birds measured in this study may not exactly reflect the values of the tissues consumed by humans exploiting these birds as a dietary resource,

a factor that should be considered before applying these data within the context of a palaeodietary baseline.

**Archaeological biota from Mývatnssveit**

*Cows: inter-site comparison.* The $\delta^{13}C$ values of archaeofaunal cow samples ranged from -22.1 to -20.3‰ (Table 3, Fig. 4). Excluding neonatal cattle, there is a barely significant difference between cattle $\delta^{13}C$ values at the four sites (ANOVA: $P = 0.4659$). Although values from Undir Sandmúla appear slightly lower than those from the other sites, the significance of this offset is difficult to assess owing to the small sample size at Undir Sandmúla (2 animals) relative to other locations. Although the majority of the vegetation–cow-bone offsets are reasonably explained by a trophic effect, it should be borne in mind in future work that some higher cow $\delta^{13}C$ values could indicate the deliberate feeding of cattle with fish bones, a practice that is documented in Icelandic historical records.

The $\delta^{15}N$ values of neonatal cattle were not higher than that of adult animals, with the exception
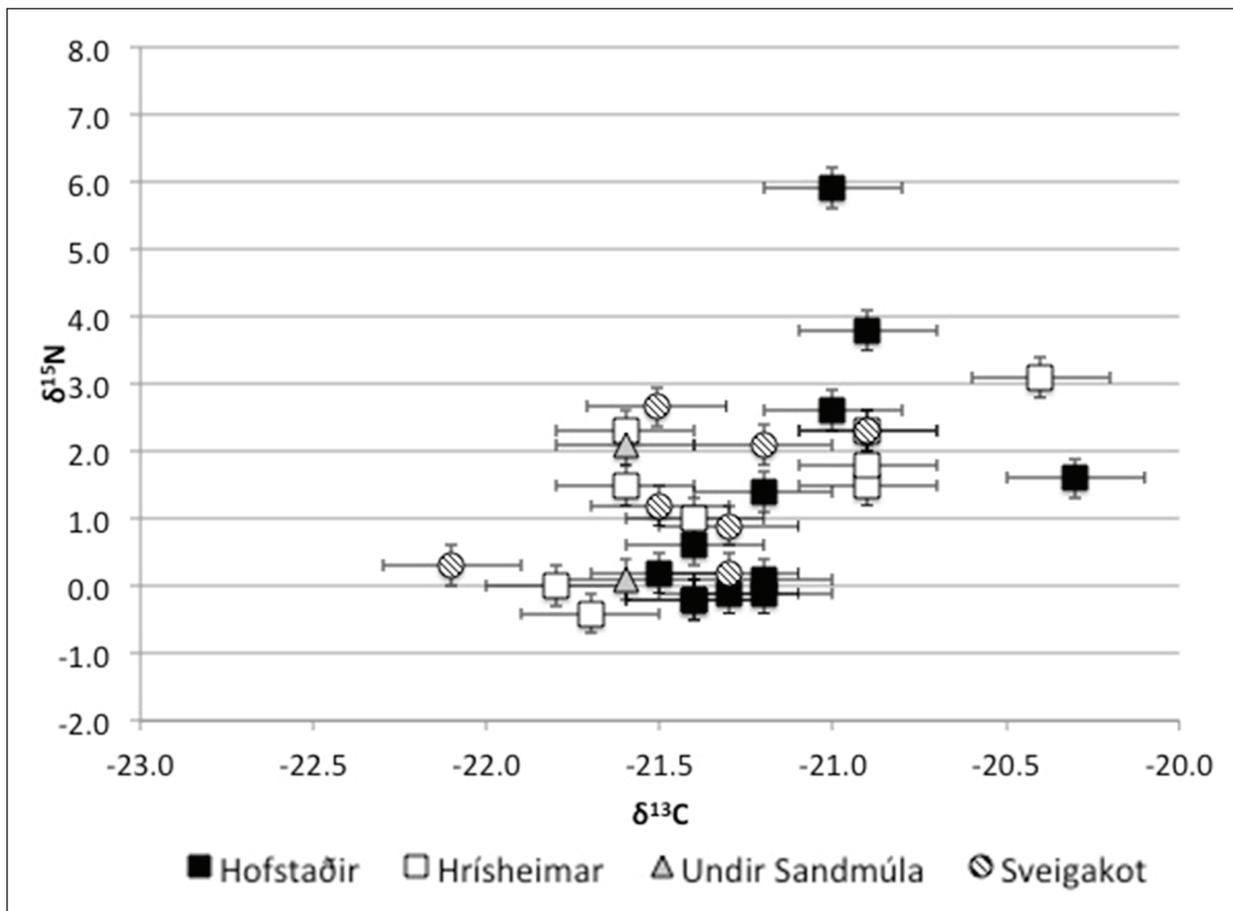


Figure 4. *Bos taurus* (cow) bone collagen isotope values for archaeofaunal samples from Mývatnssveit. Bars represent 1σ measurement precision (i.e., ± 0.2‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$).

of SUERC-3429 ($\delta^{15}$N = +5.9); this result is in contrast to the effective trophic level increase observed in neonates and suckling animals relative to the adult mother in previous studies (e.g., Ascough et al. 2012, Fuller et al. 2006). There is no statistically significant difference in the $\delta^{15}$N of non-neonatal cattle between the four sites (ANOVA: $P$ = 0.52737). However the range of $\delta^{15}$N values of cows at Sveigakot, Undir Sandmúla, and Hrísheimar (2.5‰, 2.0‰, and 3.5‰, respectively) is lower that that of cows at Hofstaðir (4‰). The farm holdings of Hofstaðir and Sveigakot (Thomson and Simpson 2007) are shown on Figure 1. It is possible that the larger range in $\delta^{15}$N values at Hofstaðir may reflect the larger size of the potential area available for grazing of animals at this site, incorporating zones with more-varied vegetation $\delta^{15}$N values.

*Ovicaprine: inter-site comparison.* In some instances, it was possible to identify samples within the ovicaprine group to species (*Ovis aries* or *Capra hircus*) on an archaeozoological basis. Where further identification was possible, there was no apparent difference between the isotope values of these species and the larger group of indeterminate ovicaprines. The range of $\delta^{13}$C values in ovicaprine samples was -22.0 to -20.8‰ (Table 3, Fig. 5). This range is not different from the range of $\delta^{13}$C

values in cattle samples, and there is no significant difference in ovicaprine $\delta^{13}$C values between sites (ANOVA: $P$ = 0.73311). The $\delta^{15}$N values of the ovicaprine sample group ranged from -1.5 to +4.0‰. The two highest values belonged to two identified neonatal animals (GU-15267 and GU-15268), resulting from the trophic offset between neonates and mothers discussed above. Exclusion of these values from the dataset gives a maximum $\delta^{15}$N value of +1.8‰. The average $\delta^{15}$N value of the archaeofaunal ovicaprine bones is hence lower than that of the cattle bones. If neonatal animals are excluded, the average cattle $\delta^{15}$N value is +1.0‰, versus an average of +0.4‰ for ovicaprines. This finding could be the result of a physiological difference between cattle and ovicaprines, although we are not aware of any studies that demonstrate that such a difference results in a $\delta^{15}$N offset between the two groups of the kind observed here. An alternative explanation is that there was a variation in the average $\delta^{15}$N value of material consumed by cattle versus that of ovicaprines. Such a dietary difference between the two groups could be the result of food selection by the organisms directly, or a difference in the type of food to which ovicaprines and cattle had access as a result of human control. The findings may therefore be suggestive of different husbandry practices
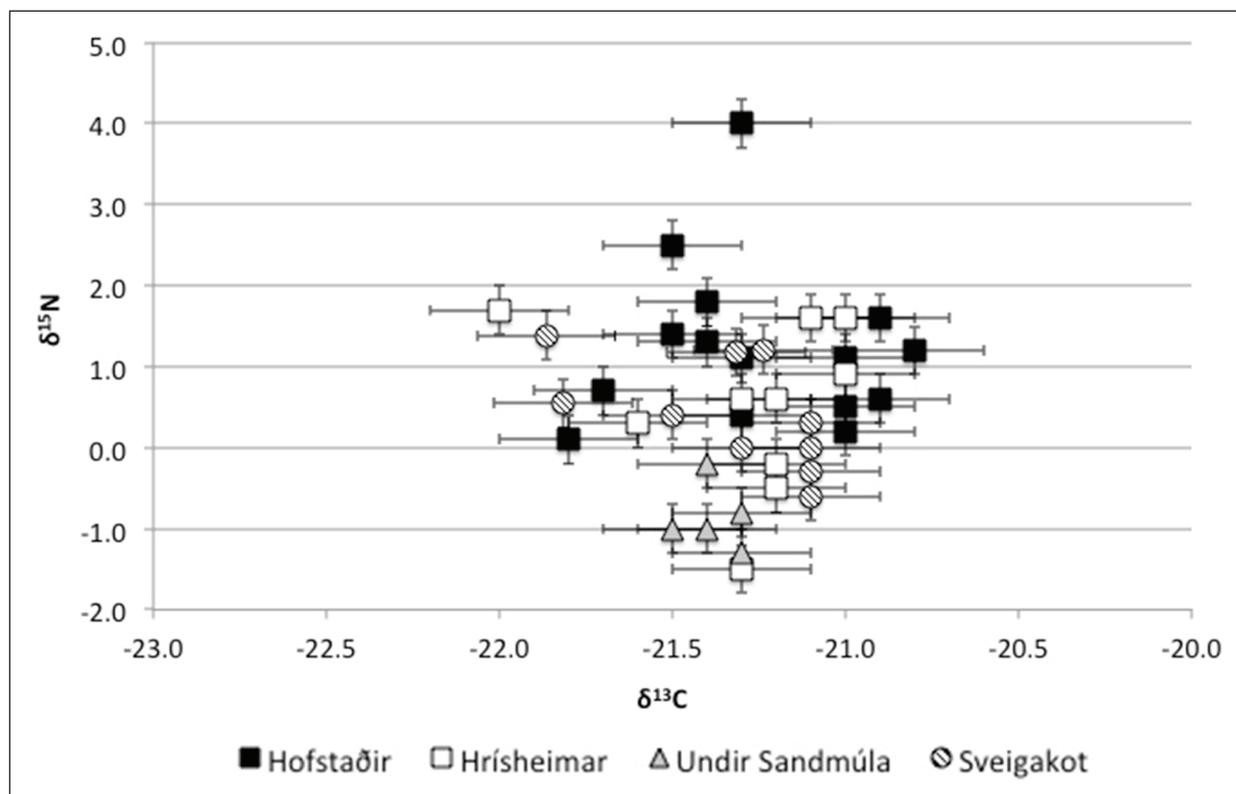


Figure 5. Ovicaprine (sheep/goat) bone collagen isotope values for archaeofaunal samples from Mývatnssveit. Bars represent 1σ measurement precision (i.e., ± 0.2‰ for $\delta^{13}$C and ± 0.3‰ for $\delta^{15}$N).

between species, such as grazing of cattle and ovicaprines in different areas of the region. Specialization in husbandry practices between species has also been used to explain similar dietary differences between domestic animal species expressed in isotopic values in previous archaeofaunal studies (e.g., Fuller et al. 2012a). The range of ovicaprine $\delta^{15}N$ values shows these animals did not frequently consume plants with the high $\delta^{15}N$ values observed at Haganes, Kálfaströnd, and Hrúteyjarnes. This finding argues against grazing of ovicaprines in intensively manured areas or zones of high natural plant $\delta^{15}N$ values.

The $\delta^{15}N$ of non-neonatal ovicaprines from Undir Sandmúla are significantly lower than animals from Hofstaðir (ANOVA, Tukey posthoc: *P* = 0.0003), Hrísheimar (ANOVA, Tukey posthoc: *P* = 0.0079), and Sveigakot (ANOVA, Tukey posthoc: *P* = 0.0152). Values from Sveigakot are significantly lower than values from Hofstaðir (ANOVA, Tukey posthoc: *P* = 0.3489). It seems likely this difference is a function of the rangeland areas of sheep and goats at Undir Sandmúla, where plant $\delta^{15}N$ values are low in modern vegetation samples. Simlarly, $\delta^{15}N$ values are also lower in animals from Sveigakot, though to a lesser extent. As observed in the cattle bones, the range in $\delta^{15}N$ values at Hofstaðir is larger than at other sites, even when neonatal animals are excluded. This result is potentially a function of site status, with greater access to herds grazing in a variety of different vegetation catchments or a wider range of fodder sources procured by the inhabitants of the site

*Pigs: inter-site comparison.* The $\delta^{13}C$ values of pig bone samples from the archaeofaunal sites ranged from -22.5 to -16.9‰, and the $\delta^{15}N$ values of these samples covers a range of -1.2 to +8.7‰ (Table 3, Fig. 6). There are significant differences between sites for non-neonatal animals for both $\delta^{13}C$ (ANOVA *P* = 0.29374) and $\delta^{15}N$ (ANOVA *P* = 0.03839). The broad range in isotope values at all three sites (Sveigakot, Hrísheimar, and Hofstaðir) from which pig bones were obtained, is likely to reflect a mixed and variable range of husbandry practices. Their diet clearly included a variety of resources and was not restricted to terrestrial material. The most distinctive difference between the sites is between the samples from Hrísheimar and those from Sveigakot and Hofstaðir. At Hrísheimar, the $\delta^{13}C$ and $\delta^{15}N$ values in the majority of sampled pig bones falls within a narrow range that is characteristic of animals existing on a diet of terrestrial vegetation. Thus, the $\delta^{13}C$ of pigs at Hrísheimar is significantly lower than those at Sveigakot (ANOVA, Tukey posthoc *P* = 0.4425) and Hofstaðir (ANOVA, Tukey posthoc *P* =0.3067), while there is no difference in $\delta^{13}C$ between pigs from Sveigakot and Hofstaðir (ANOVA, Tukey posthoc
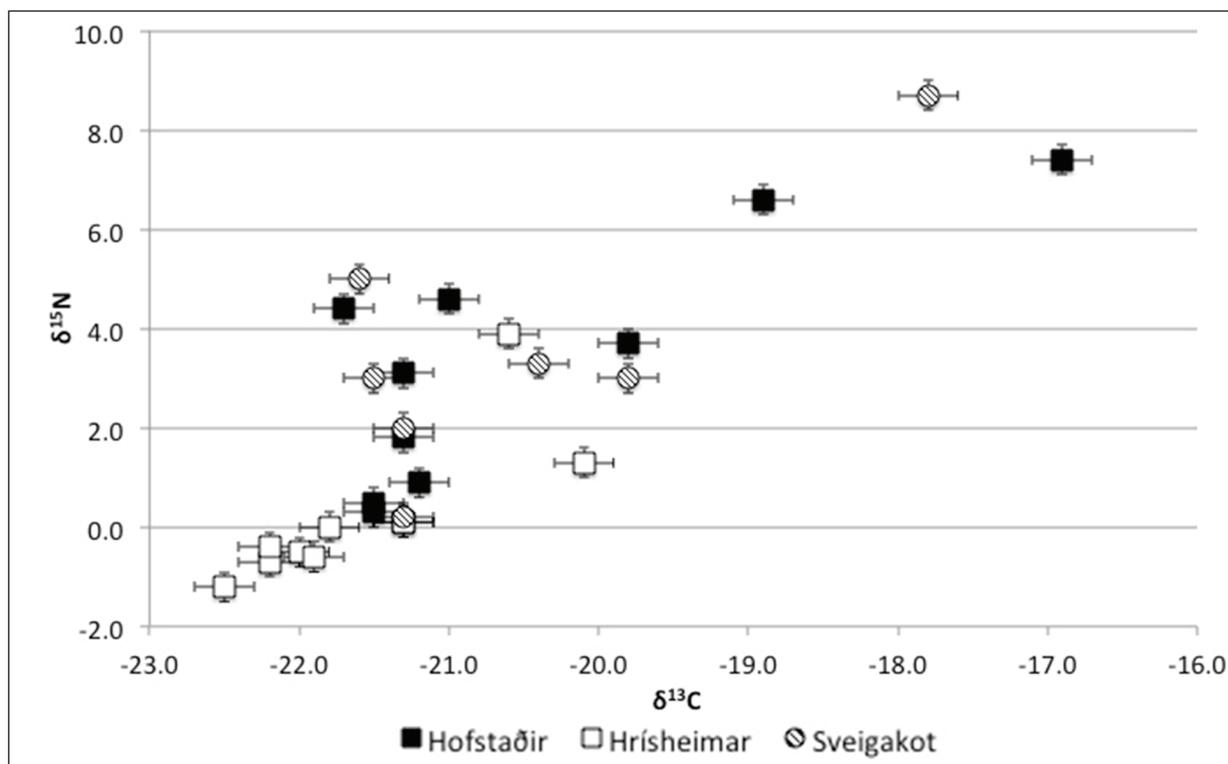


Figure 6. *Sus scrofa* (pig) bone collagen isotope values for archaeofaunal samples from Mývatnssveit. Bars represent 1σ measurement precision (i.e., ± 0.2‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$).

P.L. Ascough, M.J. Church, G.T. Cook, Á. Einarsson, T.H. McGovern, A.J. Dugmore, and K.J. Edwards

$P = 0.9842$). Similarly, the $\delta^{15}N$ of pigs at Hrísheimar is significantly lower than those at Sveigakot (ANOVA, Tukey posthoc $P = 0.058$) and Hofstaðir (ANOVA, Tukey posthoc $P = 0.0716$), while there is no difference in $\delta^{13}C$ between pigs from Sveigakot and Hofstaðir (ANOVA, Tukey posthoc $P = 0.957$). These results suggest that animal protein or non-terrestrial resources did not feature significantly in the diet of pigs from Hrísheimar, which have isotope values consistent with free-range pannage of plant material with low $\delta^{15}N$ values (such as in the modern vegetation sampled at Framengjar, Sveigakot, and Seljahjallagil). This finding could be a function of the early *landnám* date of the Hrísheimar midden layers, as previous research has suggested the use of free-range pannage pig husbandry as a means of clearing woodland (Dugmore et al. 2005; McGovern et al. 2006, 2007). In contrast, pig bone samples at Sveigakot and Hofstaðir show significantly higher $\delta^{13}C$ and $\delta^{15}N$ values that covers a wider range between animals. Clearly, non-plant material featured more heavily in the diet of pigs at these sites, which included a mix of terrestrial, freshwater, and (potentially) marine material. Animals with $\delta^{13}C$ values characteristic of terrestrial herbivores but with high $\delta^{15}N$ values could represent free-range pannage on vegetation that had high $\delta^{15}N$ values. Alternatively, these values could represent the inclusion of terrestrial animal protein in the diet of these pigs. Unfortunately, these two possibilities are not readily discriminated with bulk $\delta^{13}C$ and $\delta^{15}N$ values, although analysis of the isotopic values of amino acids may be a method that can shed further insight (e.g., Choy et al. 2010) and could be a possible focus for future work. However, where pig bone collagen $\delta^{13}C$ values are also elevated suggests inclusion of freshwater or marine protein in the diet. Potential sources of this material include fish-processing waste, fish bones, and bird eggs. The presence of freshwater protein in the diet of pigs from Mývatnssveit is also evidenced in $^{14}C$ dating, which has revealed a freshwater $^{14}C$ reservoir effect in the bones of pig samples from these sites (Ascough et al. 2010, 2012). The range of pig husbandry practices represented at Sveigakot and Hofstaðir is therefore characteristic of a varied strategy, including some animals that were fed upon domestic waste, potentially while styed.

## Wild species

The isotope values of archaeofaunal freshwater fish ($\delta^{13}C$ from -12.2 to -16.0‰, $\delta^{15}N$ from 5.6 to 6.8‰) are within the range of modern fish from Mývatn ($\delta^{13}C$ from -13.4 to -14.0‰, $\delta^{15}N$ from +5.4 to +5.8‰), although there is some variation within the group (Ascough et al. 2007, 2010). The $\delta^{13}C$ range for freshwater fish overlaps with that of previous values for archaeofaunal marine fish bone collagen (Atlantic cod from Norse and medieval period sites in northern Scotland; Russell et al. 2011), but the $\delta^{15}N$ is several per mill lower than average cod bone values from Russell et al. (2011) and other studies (e.g., Barrett et al. 2011). The $\delta^{13}C$ and $\delta^{15}N$ values of fish from freshwater systems show great site-specific variation on geographic scales; for example, Fuller et al. (2012b) found $\delta^{13}C$ values of -20.3 to -28.2‰ for freshwater fish in Belgium, while Grupe et al. (2009) measured $\delta^{13}C$ values of -11.7 to -27.4‰ for non-marine species in a brackish fjord in northern Germany. In these studies, the average $\delta^{15}N$ of freshwater fish bone collagen was several per mill higher than that of modern or archaeofaunal fish from Mývatn.

The $\delta^{13}C$ values of archaeofaunal bird bone samples from sites in Mývatnssveit were -23.6 to -9.7‰ (Table 3, Fig. 3). This range is approximately equivalent to that of the sample of modern bird bones, and similarly reflects the range in diet of the species represented. The lowest $\delta^{13}C$ values indicate a diet containing more terrestrial resources, while higher values denote increasing amounts of freshwater and/or marine material in the diet. This pattern is also reflected in the $\delta^{15}N$ values of the samples, which range from -4.9 to +15.2‰. If the resources consumed by the birds were simply terrestrial and marine in origin, a positive linear correlation between $\delta^{13}C$ and $\delta^{15}N$ values in the sample group would be expected. This is not the case, due to the confounding influence of freshwater resources in the diet of the birds. As discussed above, the isotope values for freshwater resources in the lake are highly variable. The isotope values of waterfowl in the region therefore incorporate varying proportions of terrestrial, marine, and freshwater food, whereas the isotope values for freshwater resources cover a very large range. This variability is apparent in both archaeological and modern bird samples and has implications for palaeodietary reconstructions of omnivorous organisms such as humans. Along with consumption of waterfowl themselves, exploitation of waterfowl populations by Norse populations around Mývatnssveit involved the collection of large quantities of waterfowl eggs (McGovern et al. 2006, 2007). Egg production by a bird uses nutrients obtained in the diet, and it is likely that the large variation in isotope values reflected in the bone collagen of samples analyzed in this study would be reflected in the $\delta^{13}C$ and $\delta^{15}N$ values of eggs consumed by human populations.

## Conclusions

The research presented here compiles isotope values for Norse economic resources in Mývatnssveit, representing the most comprehensive suite of archaeofaunal $\delta^{13}C$ and $\delta^{15}N$ measurements for sites in the region and anywhere in Iceland. The analyses emphasize the wide range in isotope values of resources used by the Norse settlers of Mývatnssveit. As previously noted, there is separation between the $\delta^{13}C$ values of terrestrial and freshwater resources, but considerable overlap between the $\delta^{15}N$ values of these groups (Ascough et al. 2012). This overlap means that paleodietary reconstruction of individuals in the region based solely on $\delta^{13}C$ and $\delta^{15}N$ values will always be problematic.

The results provide information that is useful to reconstructing animal husbandry practices in the study area. While herbivore bone $\delta^{13}C$ and $\delta^{15}N$ are unlikely to reveal subtle husbandry differences (e.g., small-scale differences in grazing areas or in the duration of over-winter stalling), it is clear that with sufficiently large datasets, differences and similarities between isotope values at individual sites begin to emerge. In particular, $\delta^{13}C$ and $\delta^{15}N$ measurements of pig bone enable detailed investigation of husbandry in the region as these animals are omnivores and consume a potential range of resources with large separation in terms of isotope values (e.g., terrestrial versus marine material). Within the dataset represented here, quite marked differences in pig husbandry are apparent between a relatively small number of sites.

Finally, the work highlights methodological "best practice" in the application of stable isotope analysis for archaeological research. Variation in animal management practices, rather than animals having unrestricted access to a landscape, means that particular isotopic patterns at a site could arise from a range of practices. Therefore, careful research design is required and the results need to be placed within a secure archaeological, chronological, and palaeoenvironmental framework.

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