

## Stable Isotopes, Chronology, and Bayesian Models for the Viking Archaeology of North-East Iceland

W. Derek Hamilton & Kerry L. Sayle

To cite this article: W. Derek Hamilton & Kerry L. Sayle (2019) Stable Isotopes, Chronology, and Bayesian Models for the Viking Archaeology of North-East Iceland, *The Journal of Island and Coastal Archaeology*, 14:1, 71-81, DOI: [10.1080/15564894.2017.1363097](https://doi.org/10.1080/15564894.2017.1363097)

To link to this article: <https://doi.org/10.1080/15564894.2017.1363097>



© 2017 The Author(s). Published with license by Taylor & Francis© W. Derek Hamilton and Kerry L. Sayle



Published online: 07 Nov 2017.



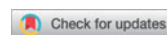
Submit your article to this journal [↗](#)



Article views: 404



View Crossmark data [↗](#)



# Stable Isotopes, Chronology, and Bayesian Models for the Viking Archaeology of North-East Iceland

W. Derek Hamilton  and Kerry L. Sayle 

*Scottish Universities Environmental Research Centre, University of Glasgow, East Kilbride, UK*

## ABSTRACT

*This paper reviews the results of a long-term research project that used stable isotope analyses ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ,  $\delta^{34}\text{S}$ ) and Bayesian mixing models to better model the chronology for a presumed Viking Age cemetery at Hofstaðir, near Lake Mývatn in north-east Iceland.  $\delta^{13}\text{C}$  and radiocarbon dating indicated that many of the individuals consumed a large amount of marine protein, which results in a marine reservoir effect (MRE), making ages older than expected. In addition to the MRE, geological activity in the region has the potential to introduce massive quantities of radioactive ‘dead’ carbon into the freshwater system, resulting in a very large freshwater reservoir effect (FRE) that can offset radiocarbon ages on the order of a few thousand years. The radiocarbon dates of organisms that derive an unknown proportion of their carbon from both marine and freshwater reservoirs are extremely difficult to ‘correct’, or, more appropriately, model. The research not only highlights the complexities of dealing with multiple reservoirs, but also how important it is to develop models that are temporally and geographically relevant to the site under study. Finally, it shows how this data can be used to inform the development of chronological models for refining the dating for archaeological activity.*

**Keywords** Iceland, palaeodiet, stable isotopes, reservoir effects, chronological modeling

Received 7 February 2017; accepted 7 July 2017.

Address correspondence to W. Derek Hamilton, Scottish Universities Environmental Research Centre, University of Glasgow, Scottish Enterprise Park, Rankine Avenue, East Kilbride G75 0QF, UK. E-mail: [Derek.Hamilton.2@glasgow.ac.uk](mailto:Derek.Hamilton.2@glasgow.ac.uk)

Color versions of one or more figures in this article are available online at [www.tandfonline.com/uica](http://www.tandfonline.com/uica). This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

## INTRODUCTION

Undertaking radiocarbon dating in coastal and island environments is oftentimes fraught with challenges that inland archaeology seldom engages, most notably the need in many cases to determine and correct for a marine reservoir effect (MRE) in samples of human and animal bone used for radiocarbon dating. In the island nation of Iceland, these complexities are amplified as the geological activity associated with the Mid-Atlantic Ridge makes the island one of the most geothermally and volcanically active in the world. In particular, hydrothermal venting has the potential to introduce massive quantities of radioactive 'dead' carbon into the freshwater system, resulting in a very large freshwater reservoir effect (FRE) that can offset radiocarbon ages on the order of a few thousand years.

While the internationally ratified marine calibration curve (Marine13; Reimer et al. 2013) can be used with a local reservoir correction ( $\Delta R$ ) to adjust for the effects of eating marine-based protein, the freshwater reservoir correction should be guided by using multiple radiocarbon measurements on terrestrial and freshwater samples from the area (and preferably time period) under consideration. However, the radiocarbon dates of organisms that derive an unknown proportion of their carbon from both marine and freshwater reservoirs are extremely difficult to 'correct', or, more appropriately, model. These circumstances highlight the importance of developing a full understanding of the local ecosystem and food web, so that individual people and animals can have the percentage of their protein that is derived from the various reservoirs accurately and precisely calculated.

This paper reviews the results of a long-term research project that ultimately used light stable isotope analyses and Bayesian mixing models to better model the chronology for a presumed Viking Age cemetery at Hofstaðir, near Lake Mývatn in north-east Iceland (Sayle et al. 2013, 2014, 2016a, 2016b). Each step of the project was

informed by the previous results and the new questions that were often raised. The research not only highlights the complexities of dealing with multiple reservoirs, but also how important it is to develop models that are temporally and geographically relevant to the site under study. Furthermore, the findings emphasized the need to have a better understanding of the ecology around Lake Mývatn, as additional factors such as sea-spray effect and midge deposition had the ability to alter isotopic baselines at the extreme local level, over just a few kilometers.

## GEOGRAPHICAL AND HISTORICAL BACKGROUND

In 1992, the North Atlantic Biocultural Organisation (NABO) was established with the intention of improving communication and collaboration between archaeology and paleoecology academics interested in the colonization of the North Atlantic region. Lake Mývatn (meaning "the lake of midges" in Icelandic) lies in the north-eastern highlands of Iceland, and, as its name suggests, is renowned for its abundant insect life. This shallow lake, located 50 km inland and at an altitude of 277 m above sea level (Figure 1), is a sanctuary for breeding waterfowl (Einarsson 2004; Gardarsson 2006). As part of NABO's "Mývatn Landscapes Project", excavations were undertaken at the sites of Hofstaðir and Skútustaðir (Figure 1), and resulted in the region being documented as an area of major archaeological importance with respect to the settlement, or *landnám*, of Viking communities in Iceland from around AD 870 onwards (Einarsson and Aldred 2011; Lucas 2009; McGovern et al. 2007; Vésteinsson 1998).

Radiocarbon dating of terrestrial animal remains and tephrochronological studies from various sites surrounding the lake have shown that settlers populated the region from the late ninth century (McGovern et al. 2006, 2007). The presence of these inhabitants is thought to have had a large



**Figure 1.** Map of Iceland and Lake Mývatn showing the location of the two sites discussed in the text (Hofstaðir and Skútustaðir).

environmental impact on the area, with the introduction of grazing livestock and rapid deforestation (Hallsdóttir 1987) leading to significant soil erosion (Arnalds et al. 1997; Dugmore et al. 2005; Lawson et al. 2007; Vésteinsson et al. 2002).

### GEOLOGY OF THE LAKE MÝVATN AREA

The area surrounding Lake Mývatn is volcanic in nature, with igneous rocks of the tholeiitic series dominating the landscape. The series is split into three subsections: 1) basaltic rocks, which are most abundant, comprising of picrite, olivine tholeiite and tholeiite; 2) intermediate rocks which include icelandite and basaltic icelandite; and 3) silicic rocks which include dacite and

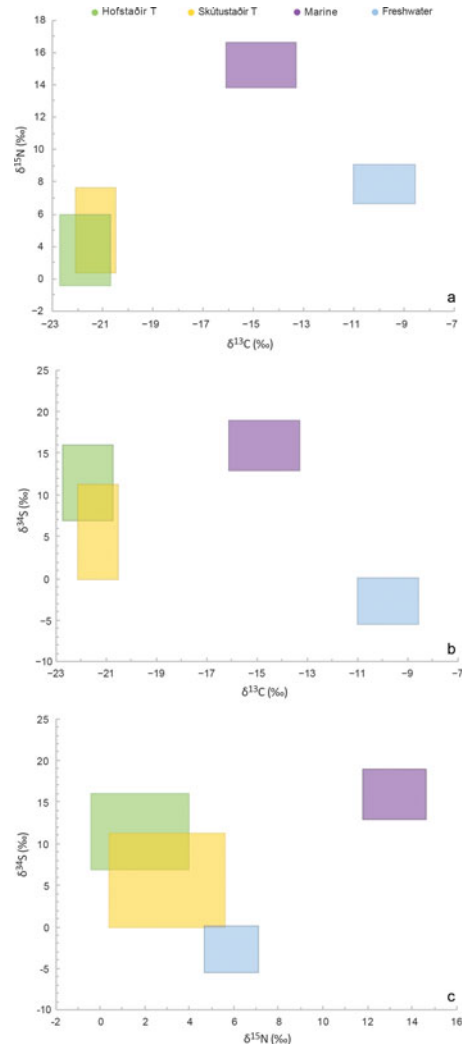
rhyolite (Jakobsson et al. 2008). Porous lava fields dominate the area, leaving the surface characteristically devoid of water. The lake has two major basins, Ytriflói (north basin), which is fed by hot springs from the Námafjall geothermal field, and Syðriflói (south basin), which is fed by cold springs along its eastern shores (Kristmannsdóttir and Ármannsson 2004). As groundwater springs supply most of Lake Mývatn's water and there is an absence of surface water in the area for it to mix with, the chemical makeup of the water entering the lake is very stable. Before draining into the River Laxá in the west, the geothermal waters provide Lake Mývatn with plentiful supplies of silica and sulphate, whilst cooler waters deliver phosphate to the lake (Kristmannsdóttir and Ármannsson 2004).

## THE PROBLEMS (AND SOLUTIONS)

It has been known that radiocarbon dating in the area around Lake Mývatn (Mývatnssveit) is complicated by the impact of marine and freshwater reservoir effects on both human and certain faunal remains (Ascough et al. 2007, 2010, 2011, 2012), which is due to the consumption of both marine fish transported from coastal sites and local freshwater resources (e.g., freshwater fish and waterfowl) (McGovern et al. 2006, 2007). The result is a high degree of overlap in the values for  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  between animals from terrestrial, marine, and freshwater systems, making it difficult to use just these two isotopes for understanding from where humans derive their dietary protein.

In 2011, the collagen from a wide range of animal bones (cow, caprine, horse, trout, charr, haddock, cod, arctic fox, pig, and various bird species) recovered from a midden deposit at Skútustaðir, which lies on the southern edge of Lake Mývatn, was analyzed for  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$ , to determine whether the addition of  $\delta^{34}\text{S}$ , to the more traditional suite of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , would enable the separation of animals receiving their carbon from terrestrial, marine, or freshwater reservoirs (Sayle et al. 2013). The results demonstrated how  $\delta^{34}\text{S}$ , in this ecosystem, allowed for clear differentiation between marine, terrestrial, and freshwater animals. The difference between  $\delta^{34}\text{S}$  was considerable between marine and freshwater animals, with marine values of  $+15.9 \pm 1.5\text{‰}$  and freshwater values of  $-2.7 \pm 1.4\text{‰}$  (Figure 2).

This new information, it was surmised, would be invaluable in better understanding human diet, and so these data were used to interpret the diet of people buried within a cemetery associated with an early chapel at Hofstaðir, which lay <10 km north-west of Skútustaðir, and ~5 km west from the shores of Lake Mývatn, along the River Laxá (Sayle et al. 2014) (Figure 3). The chapel at Hofstaðir is believed to have three phases of development, with the youngest turf construction post-dating AD 1477. Earlier buildings were erected from timber, with birch



**Figure 2.** Box plots showing the  $2\sigma$  ranges for the pairs of stable isotopes: a)  $\delta^{13}\text{C}$  vs  $\delta^{15}\text{N}$ ; b)  $\delta^{13}\text{C}$  vs  $\delta^{34}\text{S}$ ; and c)  $\delta^{15}\text{N}$  vs  $\delta^{34}\text{S}$ . The isotope measurements come from terrestrial herbivores, and both freshwater and marine fish from archaeological deposits at Hofstaðir and Skútustaðir.

wood samples thought to be part of the earliest structure, giving  $^{14}\text{C}$  ages of  $1035 \pm 35$  BP (cal AD 896–1118, 95.4% probability) and  $1015 \pm 45$  BP (cal AD 897–1155, 95.4% probability) (AA-53125 and AA-53126,





**Figure 3.** Aerial view of the Hofstaðir site (a), showing the current farm (top), remains of the excavated Viking hall (right), and chapel and cemetery under excavation (left). A majority of the skeletons were extremely well preserved (b) (images courtesy of Hildur Gestsdóttir).

respectively) (Gestsdóttir 2004). Due to the very short early settlement period, it is unclear whether the first church pre- or post-dates the abandonment of a nearby feasting hall around AD 1030; however, it is thought that the cemetery was in use between the tenth and thirteenth centuries, with all the burials predating the H-1300 tephra deposit (AD 1300). In addition, the stratigraphy at the site indicates that the intensity of burial in the cemetery was much greater in the earlier phases (Gestsdóttir 2006; Gestsdóttir and Isaksen 2011).

The ‘raw’ radiocarbon dates from nine individuals in the cemetery demonstrated the possibility for a large reservoir offset (Sayle et al. 2014). Three of the nine (SK016, SK061, and SK066) had radiocarbon dates that, when calibrated using the terrestrial curve of Reimer et al. (2013) placed their deaths pre-*landnám* (Table 1: Calibrated date).  $\delta^{13}\text{C}$  values from these nine individuals were used to estimate the percentage amount of terrestrial and non-terrestrial protein, and thus degree of marine reservoir effect on the radiocarbon measurement. Standard linear interpolation methods were used (Cook et al. 2015) to

determine the percentage diet for each type, but the fact that dietary protein for most individuals was coming from terrestrial, marine, and freshwater systems made this methodology both cumbersome and unsatisfactory. Individuals with a high percentage of freshwater protein in their diet could not be ‘corrected’ for the FRE, given the data available at the time, and their dates could only be noted as providing a *terminus post quem* for their death (Table 1: Re-calibrated date).

In 2014, a further 37 individuals from the Hofstaðir cemetery that were being radiocarbon dated had  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$  measurements made on their bone collagen (Sayle et al. 2016a). At this time, terrestrial animal bone ( $n = 39$ ) from Hofstaðir was also subjected to stable isotope analysis. Despite <10 km distance between Hofstaðir and Skútustaðir, the results for the two populations were statistically significantly different ( $p < 0.001$ ), with  $\delta^{34}\text{S}$  values for Hofstaðir herbivores  $\sim 6\%$  higher relative to those from Skútustaðir ( $\delta^{34}\text{S}$ :  $11.4 \pm 2.3\%$  versus  $5.6 \pm 2.8\%$ ) (Figure 2). While the small distance between the two sites was not viewed in the earlier study as a

**Table 1. Radiocarbon ages and various modeled dates as discussed in the text and provided in greater detail in Sayle et al. (2013, 2014, 2016a, and 2016b). The *Modeled date* is the result from Bayesian modeling after correcting for the FRE and MRE using percentages for Freshwater (%F) and Marine (%M) diet, as derived from the FRUITS computer program. These data correspond to Model 2 in Sayle et al. (2016b) where a 3.5‰ trophic shift was applied to nitrogen.**

Skeleton ID	Lab ID	<sup>14</sup> C age (yr BP)	Calibrated date	%M (±10%)	Re-calibrated date (95% probability)	%F	FRE corrected <sup>14</sup> C age (yr BP)	%M	Modeled date (95% probability)
SK007	SUERC-43994	1212 ± 29	cal AD 690-890	20	cal AD 770-1020	4 ± 3	1048 ± 139	29 ± 8	cal AD 1060-1240
SK009	SUERC-39947	1060 ± 30	cal AD 890-1030	27	cal AD 1010-1230	2 ± 2	948 ± 106	41 ± 7	cal AD 1065-1250
SK013	SUERC-41975	1123 ± 24	cal AD 780-990	8	cal AD 770-1040	5 ± 4	889 ± 177	9 ± 6	cal AD 1060-1245
SK016	SUERC-39952	2030 ± 30	160 cal BC-cal AD 60	46	cal AD 70-340*	25 ± 7	921 ± 321	17 ± 8	cal AD 1060-1245
SK047	SUERC-41982	1005 ± 24	cal AD 980-1150	7	cal AD 970-1190	5 ± 4	769 ± 181	11 ± 6	cal AD 1060-1250
SK053	SUERC-39955	1130 ± 30	cal AD 770-990	8	cal AD 770-1030	5 ± 4	881 ± 185	9 ± 6	cal AD 1060-1245
SK056	SUERC-44122	1184 ± 29	cal AD 720-950	19	cal AD 770-1040	2 ± 2	1072 ± 106	32 ± 7	cal AD 1060-1240
SK061	SUERC-39956	1560 ± 30	cal AD 420-570	23	cal AD 430-680*	10 ± 6	1101 ± 269	18 ± 8	cal AD 1060-1245
SK066	SUERC-39957	1705 ± 30	cal AD 250-410	36	cal AD 400-630*	14 ± 6	1068 ± 295	24 ± 9	cal AD 1060-1245

\*TPQs.

potential source for interpretative error, these new results cast some doubt on that assumption and resulted in much of the previous work being re-evaluated in light of the new evidence.

In any robust isotopic study, the final baseline should focus on temporally restricted data provided by the archaeological material, but as part of this expanded work, it was felt that the stable isotope values for the vegetation being consumed by the herbivores needed characterization in order to accurately calculate the baseline signal. This was only possible using modern analogues. These results suggested the local baseline was much more complex than previous research indicated, and that the  $\delta^{34}\text{S}$  value for the Mývatn region was higher than previously predicted due to a possible sea-spray effect, despite being approximately 50 km from the coast.

Delving into a study of the modern isotopic values for Lake Mývatn also served to highlight how stable isotopes can vary across relatively small distances. Lake Mývatn is renowned for its bi-annual hatching of the midge species, *Tanytarsus gracilentus*. These insects are a crucial component of the lake's ecosystem and a key food source for its aquatic and bird life (Gardarsson and Einarsson 2004; Gudbergsson 2004; Ives et al. 2008). The midges can form a thick swarm in the immediate vicinity of the lake (Figure 4), with an annual input of 1,200 to 2,500 kg of midges per hectare having been observed by Gratton et al. (2008:764), who suggested the midges can produce “a significant fertilization effect.” This phenomenon decreases logarithmically with distance from the shore, such that at 5 km from Lake Mývatn, midge deposition is negligible. This research went on to suggest that the massive deposition of midges ( $\delta^{34}\text{S}$ :  $-3.9\text{‰}$ ) in the soil in the immediate vicinity of the lake (e.g., the area of Skútustaðir) could potentially lower the sulphur value here, relative to Hofstaðir, while also serving to enrich the  $\delta^{15}\text{N}$  values through fertilization, thus serving to strengthen the conclusions of Gratton et al. (2008).

Finally, at this point in the research, results indicated several terrestrial herbivores with higher bone collagen  $\delta^{34}\text{S}$  values than their contemporaries, suggesting trade and/or movement of animals to the region from coastal areas. The broad ranging  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$  values for humans ( $-20.2\text{‰}$  to  $-17.3\text{‰}$ ,  $7.4\text{‰}$  to  $12.3\text{‰}$ , and  $5.5\text{‰}$  to  $14.9\text{‰}$ , respectively) suggested the population was consuming varied diets, while outliers within the dataset could conceivably have been migrants to the area.

Armed with a much more nuanced understanding of the expected stable isotope values from the three broad ecosystems that combine to form the wider food web for the Lake Mývatn area (terrestrial, marine, and freshwater), it was decided to revisit the radiocarbon dating of the cemetery population in an effort to refine the chronology for the chapel site (Sayle et al. 2016b). Here, we moved away from the simple linear interpolation methods that only use one or two stable isotopes, and turned to new Bayesian statistical tools for producing models for mixed diets. Specifically, the computer software program FRUITS (Food Reconstruction Using Isotopic Transferred Signals: Fernandes et al. 2014) was used to combine the available information on the baseline values for  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , and  $\delta^{34}\text{S}$  into a single model to determine the percentage of terrestrial, marine, and freshwater protein in each  $^{14}\text{C}$ -dated individual from the cemetery.

To fully ‘correct’ the radiocarbon age, it was first necessary to produce a realistic estimate for the FRE from Lake Mývatn, which required radiocarbon dating modern fish from the lake. The 12 ‘known-age’ Arctic charr and brown trout that were dated indicated there was a potentially large FRE. The radiocarbon ages for the modern material ranged from 3795 to 5329 BP, with an average reservoir estimate of  $4526 \pm 476$   $^{14}\text{C}$  years.

As illustrated in Sayle et al. (2016b), the freshwater offset was used to first correct the uncalibrated radiocarbon ages of the 46 humans that were presented in the





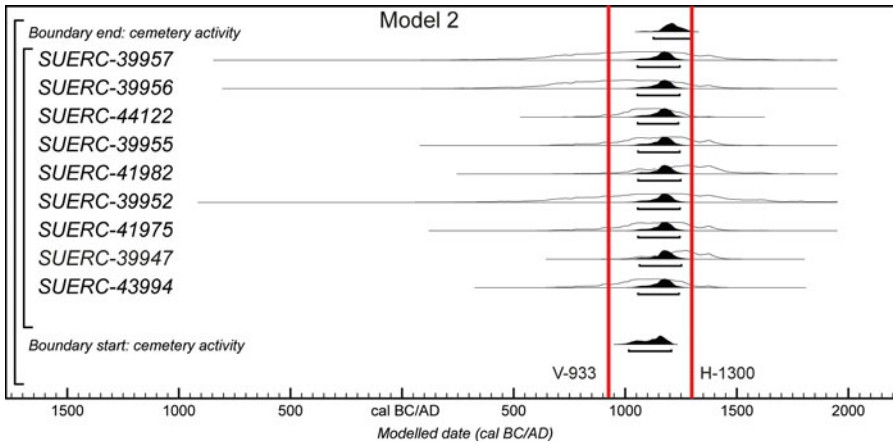
**Figure 4.** Image of Lake Mývatn looking from the south near Skútustaðir showing a swarm of midges (image courtesy of Arni Einarsson).

previous research. Here, we have reproduced the results from the nine individuals from the earliest research, with their percentage freshwater diet (%F) and FRE-corrected  $^{14}\text{C}$  age given in Table 1. Immediately apparent is how the high variability in the FRE for Lake Mývatn has greatly reduced the precision of the original radiocarbon dates, such that at this point there was some skepticism about the utility of the data from this area for providing an exemplar of the use of the FRUITS program. Nevertheless, the FRE-corrected  $^{14}\text{C}$  ages were entered into the OxCal computer program for Bayesian modeling the chronology for the cemetery. In OxCal, the Mix\_Curves function was used to calibrate the dates by mixing the appropriate percentage of the Marine13 calibration curve with the terrestrial calibration curve (IntCal13), both of Reimer et al. (2013). It is these ‘mixed curve’ calibrations that were used in subsequent Bayesian models.

The two Bayesian models of the study differed in the trophic shift applied to nitrogen ( $\delta^{15}\text{N}$ ), with the final results being very similar. Model 2, from Sayle et al. (2016b), estimated that burial in the cemetery began in *cal AD 1015–1210*, lasted for *1–230 years*, and ended in *cal AD 1125–1300 (95% probability; Figure 5)*. Another piece of chronological information was available from the cemetery, the tephrochronological dating that indicated the cemetery activity must post-date the V-933 and pre-date the H-1300 tephtras. Notably, without applying any constraints to the start or end boundaries, all 46 of the modeled dates fell within this period (AD 933–1300), thus validating the methodology and the results.

## SUMMARY

This research highlights a number of potential issues when undertaking isotopic studies in support of a radiocarbon dating



**Figure 5.** Chronological model for the Hofstaðir cemetery, as modeled in Sayle et al. 2016b. The figure shows the nine individuals that have been discussed throughout the paper, while the full model is composed of dates from all 46 of the  $^{14}\text{C}$ -dated individuals. The vertical lines indicate the dates for the V-933 and H-1300 tephras, though these dates were not used as prior information to inform the actual model, thus providing validation of the methodology as applied here.

program, especially in areas where a complex food web can lead to multiple carbon reservoirs. It shows a clear need to develop isotopic baselines as close to the site of interest as possible, and that undertaking analyses from across multiple sites of the same time period in a region has the potential to uncover nuanced intricacies in the local food web. Relatively dramatic differences were noted across a short distance, and it is possible that similar differences, not necessarily over equally short distances, might be observed in other ecosystems if these data are routinely investigated.

In addition to the scale of work that can be necessary to develop an isotopic baseline, this research has revealed just how important these baselines are for accurately calibrating/modeling radiocarbon dates. The inclusion of a third stable isotope makes these corrections extremely difficult using traditional tools, either linear interpolation of multiple pairs or even using ternary diagrams, but the development of FRUITS has made this less daunting, while also making the modeling process transparent and robust.

## ACKNOWLEDGEMENTS

*This paper is a review of research undertaken over a number of years that would not have been possible without the support of a number of individuals. The authors would like to thank the Carnegie Trust for the Universities of Scotland, who partly funded this research collaboration with funding for 'Development of a robust chronology for the archaeology around Lake Mývatn, Iceland'. We are grateful to the staff at SUERC for providing material used in early analyses and assistance with pretreatment at various stages of the process. Particular thanks go to Gordon Cook for procuring the necessary internal funding for the pilot study, as well as elements of the follow-up research. Hildur Gestsdóttir provided samples, valuable archaeological information, and the images in Figure 3. Árni Einarsson facilitated the first research trip to Iceland, provided insight into the ecosystem of Lake Mývatn, and Figure 4. A final thanks goes to Tom McGovern and all the team of NABO who showed enthusiasm for the project,*

provided additional samples, and further archaeological details about sites beyond those found in the published excavation reports.

## ORCID

W. Derek Hamilton  <http://orcid.org/0000-0003-4019-3823>

Kerry L. Sayle  <http://orcid.org/0000-0003-3492-5979>

## REFERENCES

- Arnalds, Ó., E. F. Thorarinsdóttir, S. Metusalemson, A. Johnsson, E. Gretarsson, and A. Arnason. 1997. *Soil Erosion in Iceland*. Reykjavik: Icelandic SCS and the Agricultural Research Institute.
- Ascough, P. L., M. J. Church, G. T. Cook, E. Dunbar, H. Gestsdóttir, T. H. McGovern, A. J. Dugmore, A. Friðriksson, and K. J. Edwards. 2012. Radiocarbon reservoir effects in human bone collagen from northern Iceland. *Journal of Archaeological Science* 39:2261–2271.
- Ascough, P. L., G. T. Cook, M. J. Church, A. J. Dugmore, T. H. McGovern, E. Dunbar, Á. Einarsson, A. Friðriksson, and H. Gestsdóttir. 2007. Reservoirs and radiocarbon: <sup>14</sup>C dating problems in Myvatnssveit, northern Iceland. *Radiocarbon* 49(2):947–961.
- Ascough, P. L., G. T. Cook, M. J. Church, E. Dunbar, Á. Einarsson, T. H. McGovern, A. J. Dugmore, et al. 2010. Temporal and spatial variations in freshwater <sup>14</sup>C reservoir effects: Lake Mývatn, northern Iceland. *Radiocarbon* 52(2-3):1098–1112.
- Ascough, P. L., G. T. Cook, H. Hastie, E. Dunbar, M. J. Church, Á. Einarsson, T. H. McGovern, and A. J. Dugmore. 2011. An Icelandic freshwater radiocarbon reservoir effect: Implications for lacustrine <sup>14</sup>C chronologies. *Holocene* 21(7):1073–1080.
- Cook, G. T., P. L. Ascough, C. Bonsall, W. D. Hamilton, N. Russell, K. L. Sayle, E. M. Scott, and J. M. Bownes. 2015. Best practice methodology of <sup>14</sup>C calibration of marine and mixed terrestrial/marine samples. *Quaternary Geochronology* 27:164–171.
- Dugmore, A. J., M. J. Church, P. C. Buckland, K. J. Edwards, I. Lawson, T. H. McGovern, E. Panagiotakopulu, I. A. Simpson, P. Skidmore, and G. Sveinbjarnardóttir. 2005. The Norse *landnám* on the north Atlantic islands: An environmental impact assessment. *Polar Record* 41:21–37.
- Einarsson, Á. 2004. Lake Mývatn and the River Laxá: An introduction. *Aquatic Ecology* 38:111–114.
- Einarsson, Á., and O. Aldred. 2011. The archaeological landscape of northeast Iceland: A ghost of a Viking Age society. In *Remote Sensing for Archaeological Heritage Management*: 243–258. Namur: EAC (Europae Archaeologiae Consilium) Publications.
- Fernandes, R., A. R. Millard, M. Brabec, M. J. Nadeau, P. Grootes. 2014. Food reconstruction using isotopic transferred signals (FRUITS): A Bayesian model for diet reconstruction. *PLOS ONE* 9(2):e87436.
- Gardarsson, A. 2006. Temporal processes and duck populations: Examples from Mývatn. *Hydrobiologia* 567:89–100.
- Gardarsson, A., and Á. Einarsson. 2004. Resource limitation of diving ducks at Mývatn: Food limits production. *Aquatic Ecology* 38:285–295.
- Gestsdóttir, H. 2004. *Hofstaðir 2003*. Interim Report. Fornleifastofnun Íslands. [http://www.nabohome.org/uploads/fsi/FS230-910111\\_Hofstadir\\_2003.pdf](http://www.nabohome.org/uploads/fsi/FS230-910111_Hofstadir_2003.pdf)
- Gestsdóttir, H. 2006. *Hofstaðir 2004*. Interim Report. Fornleifastofnun Íslands. [http://www.nabohome.org/uploads/fsi/FS311-910112\\_Hofstadir\\_2004.pdf](http://www.nabohome.org/uploads/fsi/FS311-910112_Hofstadir_2004.pdf)
- Gestsdóttir, H., and O. Iskasen. 2011. *Fornleifarannsóknir á kirkejugarði á Hofstöðum í Mývatnssveitsumarið 2010 (Framvinduskýrsla)*. Interim Report. Fornleifastofnun Íslands: FS455-910113.
- Gratton, C., J. Donaldson, and M. J. Vander Zanden. 2008. Ecosystem linkages between lakes and the surrounding terrestrial landscape in Northeast Iceland. *Ecosystems* 11:764–774.
- Gudbergsson, G. 2004. Arctic charr in Lake Mývatn: The centennial catch record in the light of recent stock estimates. *Aquatic Ecology* 38:271–284.
- Hallsdóttir, M. 1987. *Pollen analytical Studies of Human Influence on Vegetation in Relation to the Landnám Tepbra Layer in Southwest Iceland*. Lundqua Thesis 18, Department of Quaternary Geology. Lund: Lund University.
- Ives, A. R., Á. Einarsson, VAA Jansen, A. Gardarsson. 2008. High amplitude fluctuations and alternative dynamical states of midges in Lake Mývatn. *Nature* 452:84–87.
- Jakobsson, S. P., K. Jónasson, and I. A. Sigurdsson. 2008. The three igneous rock series of Iceland. *Jökull* 58:117–138.
- Kristmannsdóttir, H., and H. Ármannsson. 2004. Groundwater in the Lake Mývatn area,

- northern Iceland: Chemistry, origin and interaction. *Aquatic Ecology* 38:115–128.
- Lawson, I. T., F. J. Gathorne-Hardy, M. J. Church, A. J. Newton, K. J. Edwards, A. J. Dugmore, and Á. Einarsson. 2007. Environmental impacts of the Norse settlement: Palaeoenvironmental data from Mývatnssveit, northern Iceland. *Boreas* 36:1–19.
- Lucas, G. 2009. *Hofstaðir: Excavations of a Viking Age Feasting Hall in North-Eastern Iceland*. Institute of Archaeology, Reykjavík, Monograph Series 1. Reykjavík: Institute of Archaeology.
- McGovern, T. H., S. Perdikaris, Á. Einarsson, and J. Sidell. 2006. Coastal connections, local fishing, and sustainable egg harvesting: Patterns of Viking Age inland wild resource use in Mývatn district, Northern Iceland. *Environmental Archaeology* 11:187–205.
- McGovern, T. H., O. Vésteinsson, A. Friðriksson, M. Church, I. Lawson, I. A. Simpson, Á. Einarsson, et al. 2007. Landscapes of settlement in Northern Iceland: Historical ecology of human impact and climate fluctuation on the millennial scale. *American Anthropologist* 109(1):27–51.
- Reimer, P. J., E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. Bronk Ramsey, C. E. Buck, et al. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–1887.
- Sayle, K. L., G. T. Cook, P. L. Ascough, H. Gestsdóttir, W. D. Hamilton, and T. H. McGovern. 2014. Utilization of  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and  $\delta^{34}\text{S}$  analyses to understand  $^{14}\text{C}$ -Dating anomalies within a Late Viking Age community in Northeast Iceland. *Radiocarbon* 56(2):811–821.
- Sayle, K. L., G. T. Cook, P. L. Ascough, H. R. Hastie, Á. Einarsson, T. H. McGovern, M. T. Hicks, Á. Edwald, and A. Friðriksson. 2013. Application of  $\delta^{34}\text{S}$  analysis for elucidating terrestrial, marine and freshwater ecosystems: Evidence of animal movement/husbandry practices in an early Viking community around Lake Mývatn, Iceland. *Geochimica et Cosmochimica Acta* 120: 531–544.
- Sayle, K. L., W. D. Hamilton, G. T. Cook, P. L. Ascough, H. Gestsdóttir, and T. H. McGovern. 2016a. Deciphering diet and monitoring movement: Multiple stable isotope analysis of the Viking Age settlement at Hofstaðir, Lake Mývatn, Iceland. *American Journal of Physical Anthropology* 160:126–136.
- Sayle, K. L., W. D. Hamilton, H. Gestsdóttir, and G. T. Cook. 2016b. Modelling Lake Mývatn's freshwater reservoir effect: Utilisation of the statistical program FRUITS to assist in the re-interpretation of radiocarbon dates from a cemetery at Hofstaðir, north-east Iceland. *Quaternary Geochronology* 36: 1–11.
- Vésteinsson, O. 1998. Patterns of settlement in Iceland: A study in prehistory. *Saga Book* 28:1–29.
- Vésteinsson, O., T. H. McGovern, and C. Keller. 2002. Enduring impacts: Social and environmental aspects of Viking age settlement in Iceland and Greenland. *Archaeologia Islandica* 2:98–136.