Sayle, K. L. , Hamilton, W. D., Gestsdóttir, H. and Cook, G. T. (2016) 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, pp. 1-11. (doi:10.1016/j.quageo.2016.07.001)

This is the author's final accepted version.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

http://eprints.gla.ac.uk/121200/

Deposited on: 19 July 2016

Enlighten – Research publications by members of the University of Glasgow
http://eprints.gla.ac.uk

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.

Kerry L. Sayle[1]*, W. Derek Hamilton[1], Hildur Gestsdóttir[2], Gordon T. Cook[1].

[1]Scottish Universities Environmental Research Centre, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride, Scotland G75 0QF, UK

[2]Fornleifastofnun Íslands (Institute of Archaeology), Bárugata 3, 101 Reykjavík, Iceland

*corresponding author email: kerry.sayle@glasgow.ac.uk

Present address: SUERC, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 0QF, UK

Abstract

The methodology for correcting radiocarbon (^{14}C) ages for a marine reservoir effect is now reasonably well defined, while a similar correction for a freshwater reservoir effect has been demonstrated to be feasible under certain circumstances. However, adjusting radiocarbon ages to account for both sources of non-terrestrial carbon has proven challenging. Traditionally, the stable carbon (´ ^{13}C) or nitrogen (´ ^{15}N) isotope values in bone collagen can be used to determine the percentage of non-terrestrial protein in a person's diet, and the ^{14}C age can then be amended accordingly. In this study, 46 bodies excavated from the medieval cemetery at Hofstaðir, near Lake Mývatn, in north-east Iceland were ^{14}C-dated. A large number of individuals were found to pre-date the settlement (*landnám*) of Iceland in AD 871 ± 2, inferring that a proportion of their diet must have contained some non-terrestrial protein that produced a reservoir effect. As freshwater fish from Lake Mývatn and marine fish have similar bone collagen ´ ^{13}C values, using only one isotope to differentiate between the two food sources was not feasible. Therefore, ´ ^{13}C, ´ ^{15}N and ´ ^{34}S isotope values for various terrestrial animals, and marine and freshwater fish were incorporated into the Bayesian mixing modelling program FRUITS (Food Reconstruction Using Isotopic Transferred Signals) to more accurately determine the diet of each individual. Their ^{14}C ages were then corrected for both a freshwater and marine reservoir effect before Bayesian chronological modelling was employed to provide a more robust time frame for when the cemetery was in use. Previous findings suggested activity began shortly after *landnám*, however this study indicates that the cemetery was in use between the 11th and 13th centuries.

Highlights:

- Individuals were found to pre-date the settlement of Iceland in AD 871 ± 2
- Stable isotopes suggest the presence of non-terrestrial carbon is influencing ^{14}C ages
- ´ ^{13}C, ´ ^{15}N and ´ ^{34}S values were incorporated in FRUITS to more accurately determine diet
- ^{14}C ages were corrected for both freshwater and marine reservoir effects
- The chronology of the Viking Age cemetery was more accurately refined by Bayesian modelling

Keywords: Radiocarbon dating; Reservoir effects; Stable isotopes; FRUITS; Chronological modelling; Iceland.

1. Introduction

In the years since Willard Libby won the Nobel Prize in Chemistry for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science, advancements in radiocarbon (^{14}C) dating techniques, and in particular accelerator mass spectrometry (AMS), have provided archaeologists with more precise chronologies for their samples, yet at times, the interpretation of these results is still problematic. Comparatively short-lived species that have obtained their ^{14}C from atmospheric CO_2, i.e. terrestrial samples such as plant remains, seeds, grains, or terrestrial herbivore bones are ideal for radiocarbon dating as their ^{14}C has not been influenced by any additional CO_2 reservoirs and the radiocarbon ages (given in years BP, where BP is AD 1950), can be calibrated using IntCal13 (Reimer et al., 2013) to produce an accurate age range. However, a sample that has derived some or all of its carbon from a non-terrestrial reservoir can have its radiocarbon age altered by a 'reservoir effect', and hence, a correction must be implemented to generate an accurate date range. The marine ^{14}C reservoir effect (MRE), which as a global surface water average results in marine organisms appearing to be approximately 400 years older than they actually are, is the consequence of ^{14}C decaying during deep water circulation (Stuiver et al., 1986). Only surface water is capable of up-taking atmospheric CO_2 and when it mixes with waters that have not been present at the ocean surface for some time, a significant decrease in ^{14}C specific activity within that body of water, relative to the atmosphere, is observed (Stuiver and Braziunas, 1993; Ascough et al., 2005). To correctly interpret radiocarbon dates that have been influenced by a MRE, Cook et al. (2015) recommend calibrating results using the most recent marine curve together with an appropriate ” R value. This is a further local offset in the MRE (beyond the global surface water average) specific to the geographical area and time period of interest and is best determined by dating contemporaneous paired marine and terrestrial samples. However, if a sample contains both terrestrial- and marine-derived ^{14}C, e.g. humans that have consumed fish, shellfish etc. as part of their diet, then the calibration of their radiocarbon age becomes more challenging. An alternative 'mixed' calibration curve, which involves combining the calibration curves for terrestrial/atmospheric samples (IntCal13) with the calibration curve used for marine samples (Marine13) (Bronk

Ramsey, 1998) can be utilised; however for this to be a reliable correction, the percentage of marine ^{14}C in the diet has to be determined. The most commonly applied method for calculating this value is a linear interpolation approach, where the carbon stable isotope value (´ ^{13}C) of a sample is plotted between a terrestrial and marine end-member ´ ^{13}C value, which in much of Atlantic Europe, typically approximates –21.0‰ for a 100% terrestrial diet and –12.5‰ for a 100% marine diet (Arneborg et al., 1999).

A similar phenomenon has been observed in freshwater systems and has accordingly been termed the freshwater ^{14}C reservoir effect (FRE). ^{14}C in lakes originates from three main sources: atmospheric CO_2 that has entered the lake via exchange at its surface, total dissolved inorganic carbon (TDIC) from groundwater sources, and the breakdown of old organic carbon in the sedimentary system (Geyh et al., 1998). However, unlike the marine reservoir effect, a simple global average correction cannot be implemented as FREs can be large and highly variable, even within the same body of water, and therefore samples from archaeological sites that may contain radiocarbon from a freshwater source should be examined independently of each other (Geyh et al., 1998; Lanting and Van der Plicht, 1998). In a similar manner to correcting for a MRE, in cases where a species has consumed some or all of its dietary protein from a freshwater source, stable isotope analysis can be exploited to determine the proportion of freshwater ^{14}C in the diet, and the radiocarbon age can then be adjusted accordingly (Cook et al., 2001; Higham et al., 2010; Olsen et al., 2010). However, this process must be approached with great caution, especially if the reservoir effect is not uniform and if stable isotope data for archaeological freshwater fauna are unavailable. Irrespective of the source of a reservoir effect, where possible, a paired sample approach using terrestrial and marine or freshwater samples from the same archaeological context should always be utilised to provide more robust and accurate radiocarbon ages.

The purposes of this study were 1) to take a more innovative approach to calculating the percentage of non-terrestrial protein in the diets of 46 individuals from a late Viking Age cemetery at Hofstaðir in north-east Iceland using the Bayesian mixing model program FRUITS (Food Reconstruction Using Isotopic Transferred Signals) (Fernandes et al., 2014) to establish the separate proportions of terrestrial, marine and freshwater protein, and 2) to re-evaluate their radiocarbon ages by correcting for both a freshwater and marine reservoir effect by exploiting ´ ^{13}C, ´ ^{15}N and ´ ^{34}S values, rather than depending solely on ´ ^{13}C values as carried out previously (Sayle et al., 2014). The adjusted results were then incorporated into a Bayesian chronological model to produce a more robust time frame for the cemetery's use.

2. The site of Hofstaðir

Hofstaðir is situated 277 m above sea level in the highlands of north-eastern Iceland and is approximately 5 km west of Lake Mývatn (Fig. 1). Archaeological excavations began at the site in 1992 and have continued intermittently until the present day. Hofstaðir has had many phases of occupation, with tephrochronological studies suggesting the first period of activity post-dates the eruption of Veiðivötn in AD 933 ± 2, some 60 years after the well-established first settlement of Iceland (*landnám*) in AD 871 ± 2 (Grönvold et al., 1995; Lucas, 2009; Sigurgeirsson et al., 2013). Between c. AD 940–980, a feasting hall, pithouse and smithy were constructed, and over the next 50 years, the hall was expanded and further peripheral structures were added to the site. As well as evidence of textile production and metal working, a large number of livestock were reared on or within the vicinity of the site and it has been hypothesised that the hall at Hofstaðir served as a venue for religious ceremonies and feasts (Lucas, 2009). However, activity at the site was short-lived and by the time Hekla had erupted in AD 1104 it had been abandoned for approximately 70 years (Sigurgeirsson, 1998; Lucas, 2009). During the medieval and post-medieval periods, further structures, including hay silos and animal outhouses, were built into the ruins of the feasting hall (Lucas, 2009).

Excavations 80 m south-west of the feasting hall revealed the structure of a chapel and a cemetery. It is believed that there were at least three phases to the church, with the earliest constructed from timber and the youngest, which post-dates the Veiðivötn tephra of AD 1477, built from turf. Birch wood samples believed to be part of the early structure produced radiocarbon ages of 1035 ± 35 BP (AA-53125, cal AD 896–1118, 95.4% probability) and 1015 ± 45 BP (AA-53126, cal AD 899–1155, 95.4% probability), however, it is unclear if this building pre- or post-dates the abandonment of the feasting hall (Gestsdóttir, 2004). Thus far, 170 bodies have been excavated from the graveyard and all burials post-date the Veiðivötn AD 933 tephra and pre-date the eruption of Hekla in AD 1300 (Gestsdóttir, 2006; Gestsdóttir and Isaksen, 2011). The very thin tephra layer from the eruption of Hekla in AD 1104 was discovered outside the boundary wall of the cemetery, demonstrating that the graveyard was in use before the beginning of the 12th century (Gestsdóttir, *personal communication*). There were approximately 15–20 cm of soil between the H-1300 tephra and the surface at which the burials were cut. However, it is believed that these thick turf deposits

were anthropogenic and represent a deliberate sealing of the cemetery after it went out of use, possibly only a few decades before deposition of the H-1300 tephra. Additionally, there is no evidence to suggest that there were any periods of disuse; the turf deposits overlie up-cast deposits, which are most likely associated with the use of the cemetery for burials (Gestsdóttir, *personal communication*).

3. Lake Mývatn and ^{14}C-dating problems

Norse communities depended largely on marine resources and individuals living in settlements surrounding Lake Mývatn in north-eastern Iceland were no different. Although Hofstaðir lies many kilometres inland, evidence of marine mammals, including seal and porpoise bones, have been found in the Mývatn area, together with fish bones belonging to the cod family (McGovern et al., 2006, 2007). However, arctic charr (*Salvelinus alpinus*) and brown trout (*Salmo trutta*), both members of the freshwater salmon family, are in abundance in Lake Mývatn, and their bones were among the most commonly identified species found in middens excavated in the area. Since comparatively little is known about the freshwater reservoir effect in the lake, accurately determining the radiocarbon age of animals and humans from the region that have consumed both marine and freshwater protein has proven to be challenging.

Ascough et al. (2007) employed a paired-sample approach using cow bone and marine mollusc shells from the same archaeological contexts at Hofstaðir, Hrísheimar and Gásir, and concluded that an appropriate ” R value for the north Icelandic coast should be set at 111 ± 10 ^{14}C years. In the same study, the freshwater reservoir effect was evaluated using cow bone and arctic charr bones from Hrísheimar, and the offset was estimated to be between 1285 and 1830 ^{14}C years. However, Ascough et al. (2010) later noted that due to the geothermal influences in the lake there was significant variation in the FRE, with water samples from three different locations providing radiocarbon ages between 4770 and 10,605 BP, and modern freshwater fish exhibiting radiocarbon ages between 3560 and 5245 BP. Further analysis of modern lake benthic detritus, algae, aquatic plants, larvae, zooplankton and molluscs from various sites around Lake Mývatn accentuated the spatial variation within the lake (Ascough et al., 2011). Samples from around the hot spring at Helgavogur provided radiocarbon ages between 7445 and 11,215 BP, and are comparable to water samples analysed previously (Ascough et al., 2010). Samples analysed from around the cold spring at

Grjotavogur yielded radiocarbon ages between 7160 and 7255 BP, while biota taken from areas where surface water is more mixed ranged from 3545 to 4760 BP. Again, both sets of data are analogous to previously analysed water samples (Ascough et al., 2010) and the results highlight the large spatial variability in the age of organic carbon within the lake. Ascough et al. (2011) proposed using ´^{13}C and ´^{15}N isotopes to correct for Lake Mývatn's FRE, however, no correlation was found due to a lack of isotopic variation between the sample types that were analysed. Ascough et al. (2012) continued to take an isotopic approach to radiocarbon dating problems in Mývatnssveit and utilised ´^{13}C and ´^{15}N values to predict the percentage of non-terrestrial protein in the diet of seven humans and six pigs. However, when the radiocarbon ages were corrected to account for a MRE, two humans and two pigs still pre-dated *landnám*, indicating that a proportion of the non-terrestrial protein in their diets must have been derived from freshwater resources.

Utilising only ´^{13}C and ´^{15}N isotopes to interpret diet in the Lake Mývatn region is limiting as freshwater fish have exhibited ´^{13}C values that are comparable to marine fish and ´^{15}N values that are comparable to terrestrial animals (Ascough et al., 2010). However, during a study of animal bones from a midden at Skútustaðir on the southern shores of Lake Mývatn, Sayle et al. (2013) demonstrated that ´^{34}S analysis could be exploited to differentiate between animals deriving their dietary resources from terrestrial, freshwater and marine reservoirs. Marine mammals and fish were found to have high ´^{13}C and ´^{34}S values, while freshwater fish displayed high ´^{13}C and low ´^{34}S values. Sayle et al. (2014) applied this information to interpret ^{14}C-dating anomalies amongst a group of humans interred at the nearby cemetery of Hofstaðir, some of whom were found to pre-date *landnám*. Three individuals had marine-corrected calibrated dates that were still pre-*landnám* and their low ´^{34}S values confirmed the presence of an unknown proportion of freshwater protein in their diets. A further study by Sayle et al. (2016) revealed broad ranging ´^{13}C, ´^{15}N, and ´^{34}S values for an additional 37 humans from the cemetery, which suggested the population were consuming varying diets, while outliers within the dataset indicated the possibility of migrants to the area.

4. Methodology

4.1 Sampling location

The bones from the 46 adult humans analysed in this study were excavated from the cemetery at Hofstaðir in north-east Iceland (65° 612N, 17° 162W) between 1999 and 2004 (Gestsdóttir, 1999, 2001, 2002, 2003, 2004), while 12 modern freshwater Arctic charr (*Salvelinus alpinus*) and brown trout (*Salmo trutta*) were collected from various sites on Lake Mývatn during the summer of 2008 (Fig. 1).

4.2 Extraction of bone collagen

Extraction of bone collagen from the 46 human bone samples was as described in Sayle et al. (2013). Pre-treatment of modern freshwater fish involved mechanical removal of the flesh from the bones. Samples were then sonicated in a 2:1 (v/v) mixture of dichloromethane and methanol for ~ 2 hours to remove lipids before rinsing three times with deionised water (O'Connell and Hedges, 1999). A modified version of the Longin (1971) method (Dunbar et al., 2016) was then used to extract the collagen component; the samples were immersed in 1M HCl at room temperature for approximately 24 h to effect demineralisation. The acid solution was then decanted and samples were rinsed with ultra-pure water to remove contaminants before being heated gently to ~80°C in ultra-pure water. After cooling, the solution was filtered and water was removed by lyophilisation, leaving a partially hydrolysed collagen fraction (gelatin).

4.3 Radiocarbon dating and stable isotope analysis

A total of 46 human and 12 modern freshwater fish bone collagen samples were radiocarbon dated as described by Sayle et al. (2014). All calibrated dates discussed within the text are presented at 95% probability and were obtained from sample ^{14}C ages using the atmospheric IntCal13 curve (Reimer et al., 2013) and OxCal version 4.2 (Bronk Ramsey, 1995, 1998, 2001, 2009). $´^{13}C$, $´^{15}N$ and $´^{34}S$ stable isotope measurements were carried out as described in Sayle et al. (2013) and the results for the human remains have been published previously in Sayle et al. (2016). While it is common practice to make a correction for the Suess Effect when using modern terrestrial radiocarbon ages to interpret pre-industrial radiocarbon ages, no correction has been made to the radiocarbon ages of the modern freshwater fish in this study. The reasons for this decision are two-fold: 1) Arctic lakes are "supersaturated" in CO_2

and act as a source of CO_2 to the atmosphere rather than a sink (Cole et al, 1994); and 2) Lake Mývatn is frozen over for half the year (Rist, 1979), further limiting the amount of time it is possible for any carbon exchange with the atmosphere. It is because the lake is not in equilibrium with the atmosphere that no correction has been made for any possible Suess Effect.

4.4 Dietary modelling with FRUITS

To unpick the diet of the humans from Hofstaðir, the Bayesian mixing model FRUITS (Fernandes et al., 2014) was used to construct two different models, known from hereon in as Dietary Model 1 and Dietary Model 2. The program is freely available to download from http://sourceforge.net/projects/fruits/. Both models are non-routed and concentration-independent, thus only the protein fraction of the diet has been considered, and the concentration of protein for the different food groups was assumed to be 100%. Three dietary proxies – $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ – have been used in both models, and data errors fixed at ± 0.2‰, ± 0.3‰ and ± 0.6‰, respectively, in accordance with analytical errors as described by Sayle et al. (2013). Previously published stable isotope values for bone collagen from terrestrial herbivores, Atlantic cod, Arctic charr and brown trout from the archaeological record of the Lake Mývatn region were used to defined the "Terrestrial", "Marine" and "Freshwater" food groups in both models (Table 1) (Sayle et al., 2013). The models differ with respect to the value assigned for the dietary offset for nitrogen, as the trophic shift between a consumer and its food source is known to vary anywhere between +3‰ and +6‰ (Schoeninger and DeNiro, 1984; O'Connell et al., 2012; Fernandes, 2015). Carbon and sulphur offsets for both models were defined as +1 ± 0.5‰, while the nitrogen offset was defined as +6.0 ± 0.5‰ for Dietary Model 1 and +3.5 ± 0.5‰ for Dietary Model 2. No prior information from the archaeological record was added to either model.

4.5 Bayesian chronological modelling

The technique used for Bayesian chronological modelling is a form of Markov Chain Monte Carlo sampling (Buck et al., 1991, 1996) and has been applied using the program OxCal v.4.2 (http://c14.arch.ox.ac.uk/). Details of the algorithms employed by OxCal v.4.2 are available in Bronk Ramsey (1995, 1998, 2001, 2009) or from the online manual. The fit between the OxCal model and data is gauged by the A_{model} agreement index, with values

higher than 60 indicating good agreement between the model parameters and the dates (Bronk Ramsey, 1995). Resulting posterior density estimates from OxCal are in calendar years and presented in *italics* as probability ranges with end points rounded to the nearest five years. The algorithms used in the models can be derived from the OxCal keywords and bracket structure shown in the probability distribution plots.

It should be emphasised that the posterior density estimates produced by Bayesian chronological modelling and FRUITS are not absolute. They are interpretative estimates, which can and will change as further data become available, and as other researchers choose to model the existing data from different perspectives.

5. Results

5.1 Hofstaðir humans

Radiocarbon ages for the 46 sets of human remains from Hofstaðir varied from 1005 to 2030 BP and when calibrated using the IntCal 13 atmospheric calibration curve, the dates ranged from 160 cal BC to cal AD 1150 (Table 2).

5.2 Lake Mývatn fish

To gauge the magnitude of the freshwater reservoir effect in Lake Mývatn, 12 modern Arctic charr and brown trout were radiocarbon dated and the results are shown in Table 3. The offset was found to be large and variable, with radiocarbon ages for the modern material ranging from 3795 to 5329 BP, and average providing a reservoir estimate of 4526 ± 476 ^{14}C years.

5.3 FRUITS modelling and correcting for a freshwater reservoir effect

FRUITS (version 2.0 beta) was used to generate Dietary Model 1 and Dietary Model 2 for the 46 humans from Hofstaðir. For each individual, the percentages of terrestrial, marine and freshwater protein in the diet, along with the associated errors, were calculated following both models (Table S1 – Supplementary Material). These results were then used to correct for

a freshwater reservoir effect. The radiocarbon correction for the freshwater input in a person's diet (FW_{corr}) was calculated by multiplying the percentage of freshwater protein in the diet by the average ^{14}C offset (4526 ^{14}C years) measured in Lake Mývatn's modern fish (1). The error on this value ($FW_{corr/err}$) was determined by dividing the error on the percentage of freshwater input in the diet by the percentage of freshwater input in the diet, and multiplying by the correction for freshwater input (2).

$$FW_{corr} = \%FW*4526 \quad (1)$$

$$FW_{corr/err} = (\%FW_{err}/\%FW)*FW_{corr} \quad (2)$$

To calculate the corrected radiocarbon age of an individual ($^{14}C_{corr}$), the correction for freshwater input was subtracted from the original radiocarbon age (^{14}CA) (3), and the error on this correction was determined by taking the square root of the sum of the squared errors (4). Corrected radiocarbon ages for each individual using both models are shown in Table S2 (Supplementary Material).

$$^{14}C_{corr} = {}^{14}CA - FW_{corr} \quad (3)$$

$$^{14}C_{corr/err} = \bullet\ [(^{14}CA_{err})^2 + (FW_{corr/err})^2] \quad (4)$$

5.4. Correcting for a marine reservoir effect and chronological models

To account for a marine reservoir effect in Hofstaðir's humans, the freshwater corrected radiocarbon ages were calibrated in OxCal v.4.2 (Bronk Ramsey, 1995, 1998, 2001, 2009) by mixing the Marine13/IntCal13 curves (Reimer et al., 2013) using the percentage of marine protein in the diet and the associated error as previously modelled by FRUITS (Table S1), and applying a " R value of 114 ± 29 (Cook et al., 2015). The 46 dates were placed in an unordered group in the OxCal Bayesian modelling program, often referred to as a 'bounded phase', and run as two separate models – Dietary Model 1 and Dietary Model 2. The structure and assumptions of the two models are identical, and they simply assume that the cemetery at Hofstaðir was in use over a period of time with an unknown duration and a uniform distribution, or *priori*, is applied to the data. The model postulates that activity began at the site, persisted for an unknown length of time, and then ended. It also assumes that the radiocarbon dates are from a random selection of material that was deposited relatively uniformly over this period of time (Buck et al., 1992). A second bounded phase model was

also constructed, where the start and end boundaries were constrained by the addition of the prior knowledge that they must lie between Veiðivötn tephra of AD 933 and the Hekla tephra of AD 1300. The modelled dates, with and without tephra boundaries for Dietary Model 1 and Dietary Model 2, are shown in Table 4.

6. Discussion

Archaeologists believe the cemetery at Hofstaðir is of Christian origin, yet 35 of the 46 people that were radiocarbon dated in this study pre-date the introduction of Christianity to Iceland in AD 1000, when calibrated using the IntCal 13 atmospheric calibration curve. Additionally, 14 individuals were found to have calibrated radiocarbon dates that pre-date the *landnám* tephra of AD 871 ± 2. Stable isotope analysis suggests this population was consuming varying amounts of terrestrial, freshwater and marine protein, and that the presence of non-terrestrial carbon within the diet is reflected in the radiocarbon ages of the Hofstaðir community. In situations where we can be sure that the contribution of non-terrestrial protein to a person's diet is exclusively from a marine or freshwater environment, linear interpolation between dietary end-members using $\delta^{13}C$ or $\delta^{15}N$ values, respectively, can be an effective means of calculating the quantity of this resource (Arneborg et al., 1999; Cook et al., 2001). However, since stable isotope analyses confirmed that the people of Hofstaðir may have been consuming more than one source of non-terrestrial protein, applying this method to correct their radiocarbon dates is not ideal (Sayle et al., 2014; Cook et al., 2015). The introduction of the Bayesian mixing modelling program FRUITS has enabled us to more accurately determine the proportion of protein from each food group. While both models demonstrate that the majority of protein in each person's diet had been obtained from terrestrial resources, there is an increase in this value between the two models in favour of Dietary Model 1. With a few exceptions, the bulk of the remainder of the dietary protein is sourced from the marine food web. However, FRUITS apportions a higher percentage of marine protein and a lower percentage of freshwater protein to an individual's diet when a smaller trophic shift value for nitrogen is applied, as observed in Dietary Model 2 (Table S1).

The amount of terrestrial, marine and freshwater dietary protein for all 46 individuals has been modelled using FRUITS, and their freshwater (and marine) corrected radiocarbon dates have been re-calibrated (Table S2), however, the discussion will focus mainly on the nine individuals previously analysed by Sayle et al. (2014) and re-evaluated by Cook et al. (2015).

In keeping with previous findings by Ascough et al. (2007, 2010, 2011), modern fish from Lake Mývatn were affected by a large FRE, and exhibited radiocarbon dates that were not only spatially variable but also differed by *ca*. 1500 ^{14}C years within the same species. Ideally, a FRE would be estimated using the paired sample approach of Russell et al. (2010), however, such samples were not available. Given the extremely high variability observed in modern fish from Lake Mývatn, it was assumed this would encompass any variability that was noted through time. The radiocarbon dates for the modern fish are also comparable with two non-paired Viking Age fish bone samples dated from Hofstaðir (SUERC-11539: 4930 ± 35 BP and SUERC-11540: 4675 ± 35 BP), and are in keeping with the FRE estimation by Ascough et al. (2010) of at least 3500 ^{14}C years. Cook et al. (2015) calculated the percentage of marine protein in the diet of three individuals deemed to have consumed a predominately terrestrial diet (SUERC-41975, SUERC-41982 and SUERC-39955), and the amount was analogous to the value calculated in both dietary models using FRUITS. However, their radiocarbon dates were not corrected for a freshwater offset. Dietary Models 1 and 2 suggest that 5 to 6% (± 4%) of the protein in these people's diets was from a freshwater source, and since the average radiocarbon age of modern freshwater fish measured in this study is 4526 ± 476 ^{14}C years, this could represent an offset of between *ca*. 40 and 500 ^{14}C years. Similarly, the three individuals who had consumed a significant proportion of marine protein (SUERC-43994, SUERC-44122 and SUERC-39947) had comparable modelled percentage marine diets, yet FRUITS determined that they had additionally consumed up to 10% more freshwater protein. Stable isotope analyses and radiocarbon dating previously confirmed that the remaining three individuals (SUERC-39952, SUERC-39956 and SUERC-39957) had been consuming a large amount of freshwater protein; however linear interpolation of ´ ^{13}C values could only provide *terminus post quem* re-calibrated dates for these people. As the global average marine offset is ~400 ^{14}C years (Stuiver et al., 1986), an offset of ~100 ^{14}C years would represent an intake of ~25% marine protein, whereas consumption of ~25% freshwater protein at Lake Mývatn would equate to an offset of ~1250 ^{14}C years. Therefore, even if Cook et al. (2015) had assumed a 100% marine diet for SUERC-39952 and SUERC-39957, their re-calibrated dates would still pre-date *landnám*. In Dietary Model 1, FRUITS demonstrated that while there is an intake of some marine protein in the diet, SUERC-39952, SUERC-39956 and SUERC-39957, all had a preference for freshwater protein. However in Dietary Model 2, while the percentage of freshwater protein for SUERC-39956 and SUERC-39957 is high, both show a preference for marine protein.

After adjusting for a freshwater reservoir effect, all 46 individuals were found to have an older corrected radiocarbon age when Dietary Model 2 was employed rather than when Dietary Model 1 was utilised (Table 4). This is due to the smaller trophic shift value for nitrogen in Dietary Model 2, and the subsequent lower percentage of freshwater protein being apportioned to an individual's diet. Since consumption of 1% freshwater protein from Lake Mývatn equates to an offset of ~50 ^{14}C years compared to ~4 ^{14}C years for consumption of 1% marine protein, the decrease in the percentage of freshwater protein in Dietary Model 2 means that there will be less of an offset to adjust for, and therefore corrected radiocarbon ages will be older. Figures 2A, 3A and 4 are abridged versions of the full models given in the Supplementary Material (Figs. S1–S4), and this has been done to facilitate the discussion of the nine individuals previously published. All the presented models have good agreement between the radiocarbon dates and the assumption that the burials represent a single phase of activity. Bayesian analysis of corrected radiocarbon dates generated via Dietary Model 1 estimates that burial in the cemetery began in *cal AD 1050–1255* (*95% probability*; Fig. 2A; *start: cemetery activity (Model 1)*), lasted for *1–200 years* (*95% probability*; Fig. 2B; *span: cemetery activity (Model 1)*), and ended in *cal AD 1170–1300* (*95% probability*; Fig. 2A; *end: cemetery activity (Model 1)*).

When Dietary Model 2 was employed, Bayesian analysis estimates activity began at the cemetery in *cal AD 1015–1210* (*95% probability*; Fig. 3A; *start: cemetery activity (Model 2)*), lasted for *1–230 years* (*95% probability*; Fig. 3B; *span: cemetery activity (Model 2)*), and ended in *cal AD 1125–1300* (*95% probability*; Fig. 3A; *end: cemetery activity (Model 2)*). Notably, before any constraints were applied to the start and end boundaries, all 46 modelled dates in both dietary models fall within the period between the V-933 and H-1300 tephras.

When the tephra boundaries were applied to the Bayesian models, there was very little change in the start and end dates for activity at the cemetery, with calibrated dates shifting to a slightly earlier period. When Dietary Model 1 was utilised, Bayesian analysis estimates activity began at the cemetery in *cal AD 1040–1250* (*95% probability*; Fig. 4A; *start: cemetery activity (Model 1 - tephra)*) and ended in *cal AD 1180–1300* (*95% probability*; Fig. 4A; *end: cemetery activity (Model 1 - tephra)*). When Dietary Model 2 was employed, activity at the cemetery was estimated to start in *cal AD 1015–1210* (*95% probability*; Fig. 4B; *start: cemetery activity (Model 2 - tephra)*) and ended in *cal AD 1130–1295* (*95% probability*; Fig. 4B; *end: cemetery activity (Model 2 - tephra)*).

Overall, when Dietary Model 1 was used, Bayesian chronological analysis suggests that activity at the cemetery started in the middle of the 11th century, but it began approximately 35 years earlier when Dietary Model 2 was applied. In both cases, activity ended just before the eruption of Hekla in AD 1300 (Fig. 5).

Previous analysis of the stable isotope values for nine individuals from Hofstaðir and the subsequent re-calibration of their radiocarbon ages demonstrated that the cemetery was probably in use just after *landnám* until the 13th century (Sayle et al., 2014; Cook et al., 2015). However, this study has shown that had the incorporation of FRUITS not been implemented, an incorrect chronology for many of the burials would have been assumed. SUERC-41975, SUERC-41982 and SUERC-39955, who had all eaten a terrestrial-based diet, were thought to have died between cal AD 770–1190. However, when Dietary Model 1 was applied, Bayesian modelled dates ranged from *cal AD 1125–1280*, and when Dietary Model 2 was employed, modelled dates ranged from *cal AD 1060–1250*, and so shortening the use of the cemetery considerably. FRUITS has revealed that these individuals consumed a large enough proportion of freshwater-derived protein to produce a significant effect on their radiocarbon age, thus making any interpretations of their chronology *importantly* wrong (Bayliss et al., 2007). Similarly, when the radiocarbon ages for SUERC-43994, SUERC-39947 and SUERC-44122 were originally re-calibrated to account for a marine reservoir effect, the dates of death ranged from cal AD 770–1230. However, FRUITS demonstrated that these individuals had also eaten some freshwater protein, and when Dietary Model 1 was implemented, Bayesian modelled dates ranged from *cal AD 1120–1280*, and from *cal AD 1060–1250* when Dietary Model 2 was utilised. At the outset of this study, the authors were unable to more accurately determine a date of death for individuals that had consumed a large proportion of freshwater protein (SUERC-39952, SUERC-39956 and SUERC-39957), and even after accounting for a marine reservoir effect, the dates of death ranged from cal AD 70–680, which are significantly pre-*landnám* (Sayle et al., 2014; Cook et al., 2015). After re-calibrating for both a freshwater and marine reservoir effect, these three individuals gave modelled dates of *cal AD 1125–1280* (Dietary Model 1) and *cal AD 1060–1245* (Dietary Model 2). When tephra boundaries were applied to the Bayesian models, there was no appreciable difference to the modelled dates for any of the nine individuals.

7. Conclusions

Remodelling the dataset from Hofstaðir using FRUITS and Bayesian chronological analysis has not only presented archaeologists with a better understanding of past diet, but has provided a shorter and more precise time frame for when the cemetery was in use. Nevertheless, while the results presented here do fall within the known tephrochronological boundaries, the re-interpretation of radiocarbon dates from Iceland using the above methods are not without fault. In this study, Lake Mývatn's large and variable freshwater reservoir effect has had a limiting effect on the results, such that further refinement by examining temporal variation between the burials at Hofstaðir cannot be established. However, the utilisation of FRUITS when numerous reservoir effects are present is a much improved approach to age determination, and subsequent modelling of calendrical dates, than previously presented. The authors recommend that where possible, when interpreting radiocarbon dates, $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values, in conjunction with analysis using a program such as FRUITS, should be exploited to calculate the percentage of non-terrestrial protein in the diet, rather than depending solely on carbon isotope values to correct for reservoir effects. By doing this, and clearly documenting all of the modelling assumptions, a high degree of transparency can be ensured.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for profit sectors. The authors would like to thank the archaeologists involved in excavation at Hofstaðir, which was funded in part by the US National Science Foundation program "Landscapes of Settlement: Historical Ecology in Northern Iceland" (grant number 0001026), the Icelandic Centre for Research (RANNÍS), the Nordic Research Councils for the Humanities (NOS-H) and the National Geographic Society. The authors also wish to thank Professor Marian Scott for providing support with the FRE correction, Dr Philippa Ascough for supplying modern freshwater fish samples from Lake Mývatn, Helen Kinch for pre-treatment of the fish bones, and Dr Tony Krus for comments on the manuscript. Finally, thanks are due to the staff of the SUERC AMS Facility for ^{14}C measurements.

References

Ambrose SH. 1990. Preparation and characterization of bone and tooth collagen for isotopic analysis. Journal of Archaeological Science 17:431–451.

Arneborg J, Heinemeier J, Lynnerup N, Nielsen HL, Rud N, Sveinbjörnsdóttir ÁE. 1999. Change of Diet of the Greenland Vikings Determined from Stable Isotope Analysis and ^{14}C Dating of their Bones. Radiocarbon 41(2):157–168.

Ascough PL, Cook GT, Dugmore AJ. 2005. Methodological approaches to determining the marine radiocarbon reservoir effect. Progress in Physical Geography 29(4):523–547.

Ascough PL, Cook GT, Church MJ, Dugmore AJ, McGovern TH, Dunbar E, Einarsson Á, Friðriksson A, Gestsdóttir H. 2007. Reservoirs and radiocarbon: ^{14}C dating problems in Myvatnssveit, northern Iceland. Radiocarbon 49(2):947–961.

Ascough PL, Cook GT, Church MJ, Dunbar E, Einarsson Á, McGovern TH, Dugmore AJ, Perdikaris S, Hastie H, Friðriksson A, Gestsdóttir H. 2010. Temporal and spatial variations in freshwater ^{14}C Reservoir Effects: Lake Mývatn, northern Iceland. Radiocarbon 52(2–3): 1098–1112.

Ascough PL, Cook GT, Hastie H, Dunbar E, Church MJ, Einarsson Á, McGovern TH, Dugmore AJ. 2011. An Icelandic Freshwater Radiocarbon Reservoir Effect: Implications for lacustrine ^{14}C chronologies. The Holocene 21(7):1073–1080.

Ascough, P.L., Church, M.J., Cook, G.T., Dunbar, E., Gestsdóttir, H., McGovern, T.H., Dugmore, A.J., Friðriksson, A., Edwards, K.J. 2012. Radiocarbon reservoir effects in human bone collagen from northern Iceland. Journal of Archaeological Science 39:2261–2271.

Bayliss, A., Bronk Ramsey, C., van der Plicht, J., Whittle, A., 2007. Bradshaw and Bayes: towards a timetable for the Neolithic. Cambridge Archaeological Journal 17(1 suppl.):1–28.

Bronk Ramsey C. 1995. Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program. Radiocarbon 37(2):425–430.

Bronk Ramsey C. 1998. Probability and dating. Radiocarbon 40(1):461–474.

Bronk Ramsey C. 2001. Development of the radiocarbon program OxCal. Radiocarbon 43(2A):355–363.

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1):337–360.

Buck CE, Kenworthy JB, Litton CD, Smith AFM. 1991. Combining archaeological and radiocarbon information: A Bayesian approach to calibration. Antiquity 65(249):808-21.

Buck CE, Litton CD, Smith AFM. 1992. Calibration of radiocarbon results pertaining to related archaeological events. Journal of Archaeological Science 19:497–512.

Buck CE, Cavanagh WG, Litton CD. 1996. Bayesian approach to interpreting archaeological data. Chichester: John Wiley & Sons, Ltd.

Cole JJ, Caraco NF, Kling GW, Kratz TK. 1994. Carbon Dioxide Supersaturation in the Surface Waters of Lakes. Science 265:1568–1570.

Cook GT, Bonsall C, Hedges REM, McSweeney K, Boroneant V, Pettitt PB. 2001. A freshwater diet-derived reservoir effect at the Stone Age sites in the Iron Gates gorge. Radiocarbon 43(2A):453–460.

Cook GT, Ascough PL, Bonsall C, Hamilton WD, Russell N, Sayle KL, Scott EM, Bownes JM. 2015. Best practice methodology of ^{14}C Calibration of marine and mixed terrestrial/marine samples. Quaternary Geochronology 27:164–171.

DeNiro MJ. 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317:806–809.

Dunbar E, Cook GT, Naysmith P, Tripney BG, Xu S. 2016. AMS ^{14}C Dating at the Scottish Universities Environmental Research Centre (SUERC) Radiocarbon Dating Laboratory. Radiocarbon 58(1):9–23.

Fernandes R, Millard AR, Brabec M, Nadeau M-J, Grootes P. 2014. Food Reconstruction Using Isotopic Transferred Signals (FRUITS): A Bayesian Model for Diet Reconstruction. PLoS ONE 9(2):e87436.

Fernandes R. 2015. A Simple (R) model to predict the source of dietary carbon in individual consumers. Archaeometery. DOI: 10.1111/arcm.12193.

Gestsdóttir H. 1999. The Medieval Churchyard. In Lucas, G (ed.) Hofstaðir 1999. Interim Report. Fornleifastofnun Íslands: FS102–91017:44–54.

Gestsdóttir H. 2001. The Medieval Chapel and Churchyard. In Lucas, G (ed.) Hofstaðir 2000. Interim Report. Fornleifastofnun Íslands: FS130-91018:21–25.

Gestsdóttir H. 2002. Area Z. In Lucas, G (ed.) Hofstaðir 2001. Interim Report. Fornleifastofnun Íslands: FS167-91019:29–34.

Gestsdóttir H. 2003. The Chapel. In Lucas, G (ed.) Hofstaðir 2002. Interim Report. Fornleifastofnun Íslands: FS193-910110:26–29.

Gestsdóttir H. 2004. Hofstaðir 2003. Interim Report. Fornleifastofnun Íslands: FS230-910111.

Gestsdóttir H. 2006. Hofstaðir 2004. Interim Report. Fornleifastofnun Íslands: FS311-910112.

Gestsdóttir H, Iskasen O. 2011. Fornleifarannsóknir á kirkjugarði á Hofstöðum í Mývatnssveit sumarið 2010 (Framvinduskýrsla). Interim Report. Fornleifastofnun Íslands: FS455-910113.

Geyh MA, Schotterer U, Grosjean M. 1998. Temporal Changes of the ^{14}C Reservoir Effect in Lakes. Radiocarbon 40(2):921–931.

Grönvold K, Óskarsson N, Johnsen SJ, Clausen HB, Hammer CU, Bond G, Bard E. 1995. Tephra layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land-based sediments. Earth and Planetary Science Letters 135(1–4):149–155.

Higham T, Warren R, Belinskij A, Härke H, Wood R. 2010. Radiocarbon Dating, Stable Isotope Analysis, and Diet-Derived Offsets in ^{14}C Ages from the Klin-Yar Site, Russian North Caucasus. Radiocarbon 52(2):653–670.

Lanting JN, Van der Plicht J. 1998. Reservoir Effects and Apparent ^{14}C-Ages. The Journal of Irish Archaeology 9:151–165.

Longin R. 1971. New method of collagen extraction for radiocarbon dating. Nature 230(5291):241–242.

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 TH, Perdikaris S, Einarsson Á, Sidell J. 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 TH, Vésteinsson O, Friðriksson A, Church M, Lawson I, Simpson IA, Einarsson, Á, Dugmore A, Cook G, Perdikaris S, Edwards KJ, Thomson AM, Adderley WP, Newton A, Lucas G, Edvardsson R, Aldred O, Dunbar E. 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.

O'Connell TC, Hedges REM. 1999. Investigations into the Effect of Diet on Modern Human Hair Isotopic Values. American Journal of Physical Anthropology 108:409–425.

O'Connell TC, Kneale CJ, Tasevska N, Kuhnle GGC. 2012. The Diet-Body Offset in Human Nitrogen Isotopic Values: A Controlled Dietary Study. American Journal of Physical Anthropology 149:426–434.

Olsen J, Heinemeier J, Lüebke H, Lüth F, Terberger T. 2010. Dietary Habits and Freshwater Reservoir Effects in Bones from a Neolithic NE German Cemetery. Radiocarbon 52(2):635–644.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. Radiocarbon 55(4):1869–1887.

Rist S. 1979. Water level fluctuations and ice cover of Lake Myvatn. Oikos 32:67–81.

Russell N, Cook GT, Ascough PL, Dugmore AJ. 2010. Spatial variation in the MRE throughout the Scottish Post-Roman to late medieval period: North Sea values (500 – 1350 BP). Radiocarbon 52:1166–1181.

Sayle KL, Cook GT, Ascough PL, Hastie HR, Einarsson Á, McGovern TH, Hicks MT, Edwald Á, Friðriksson A. 2013. Application of ^{34}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 KL, Cook GT, Ascough PL, Gestsdóttir H, Hamilton WD, McGovern TH. 2014. Utilization Of ´ ^{13}C, ´ ^{15}N and ´ ^{34}S Analyses To Understand ^{14}C-Dating Anomalies Within A Late Viking Age Community In Northeast Iceland. Radiocarbon 56(2):811–821.

Sayle KL, WD Hamilton, Cook GT, Ascough PL, Gestsdóttir H, McGovern TH. 2016. Deciphering Diet and Monitoring Movement: Multiple Stable Isotope Analysis of the Viking Age Settlement at Hofstaðir, Lake Mývatn, Iceland. American Journal of Physical Anthropology. DOI: 10.1002/ajpa.22939.

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

Sigurgeirsson M. 1998. GjÌ skulagarannsÌ knir á Hofstöðum 1992–1997. Archaeologia Islandica 1:110–118.

Sigurgeirsson M, Hauptfleisch U, Newton A, Einarsson Á. 2013. Dating of the Viking Age Landnám Tephra Sequence in Lake Mývatn Sediment, North Iceland. Journal of the North Atlantic 21:1–11.

Stuiver M, Pearson GW, Braziunas TF. 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. Radiocarbon 28(2B):980–1021.

Stuiver M, Braziunas TF. 1993. Modelling atmospheric ^{14}C influences and ^{14}C ages of marine samples to 10,000 BC. Radiocarbon 35(1):137–189.

Tables

Table 1: ´^{13}C, ´^{15}N and ´^{34}S bone collagen values for food groups incorporated into FRUITS.

Food Group	´^{13}C [‰]	´^{15}N [‰]	´^{34}S [‰]
Terrestrial	–21.7 ± 0.5	1.8 ± 1.1	11.4 ± 2.3
Marine	–14.3 ± 0.4	13.4 ± 0.8	15.8 ± 1.8
Freshwater	–9.8 ± 0.6	5.9 ± 0.6	–2.7 ± 1.4

Table 2: Radiocarbon ages and stable isotope results for Hofstaðir human bone collagen. †Indicates ^{14}C ages previously published in Sayle et al. (2014). Age ranges are based on measured ^{14}C ages following calibration with the IntCal13 atmospheric calibration curve and OxCal v.4.2. Calibrated dates are rounded outwards to 10 years. Stable isotope results are previously published in Sayle et al. (2016).

Reporting No.	Skeleton No.	´^{13}C [‰]	´^{15}N [‰]	´^{34}S [‰]	Radiocarbon Age (BP)	Calibrated date (95% probability)
SUERC-44824	SK001	–19.7	8.8	11.8	1149 ± 35	cal AD 770–980
SUERC-43991	SK002	–19.5	9.9	11.2	1309 ± 29	cal AD 650–770
SUERC-43992	SK003	–19.9	8.9	12.0	1097 ± 29	cal AD 880–1020
SUERC-41973	SK004	–19.0	10.2	8.2	1395 ± 24	cal AD 600–670
SUERC-43993	SK005	–19.7	10.0	11.0	1232 ± 29	cal AD 680–890
SUERC-43994†	SK007	–19.2	10.6	12.3	1212 ± 29	cal AD 690–890
SUERC-41974	SK008	–19.7	9.4	14.1	1183 ± 24	cal AD 770–950
SUERC-39947†	SK009	–18.7	12.3	13.8	1060 ± 30	cal AD 890–1030

SUERC-43995	SK010	–18.9	10.3	13.1	1163 ± 29	cal AD 770–970
SUERC-39951	SK011	–19.8	9.8	12.8	1170 ± 30	cal AD 770–970
SUERC-43996	SK012	–19.3	10.1	12.9	1109 ± 29	cal AD 880–1020
SUERC-41975[†]	SK013	–20.1	7.4	11.6	1123 ± 24	cal AD 780–990
SUERC-43997	SK014	–19.7	9.8	12.6	1075 ± 29	cal AD 890–1020
SUERC-44001	SK015	–20.0	9.7	12.8	1196 ± 29	cal AD 720–940
SUERC-39952[†]	SK016	–17.3	10.3	5.5	2030 ± 30	160 cal BC – cal AD 60
SUERC-39953	SK017	–19.9	9.7	12.8	1120 ± 30	cal AD 770–1000
SUERC-39954	SK018	–19.5	9.7	8.3	1340 ± 30	cal AD 640–770
SUERC-44002	SK019	–19.2	9.8	7.9	1402 ± 30	cal AD 590–670
SUERC-44003	SK020	–18.9	9.1	7.9	1461 ± 29	cal AD 550–650
SUERC-41976	SK021	–19.9	10.0	10.0	1117 ± 20	cal AD 890–980
SUERC-41977	SK022	–19.5	8.8	13.6	1161 ± 24	cal AD 770–970
SUERC-44004	SK024	–20.1	9.2	11.1	1089 ± 29	cal AD 890–1020
SUERC-44005	SK025	–19.1	10.2	12.8	1218 ± 28	cal AD 690–890
SUERC-44006	SK026	–19.6	10.4	12.8	1111 ± 28	cal AD 870–1020
SUERC-41981	SK027	–20.2	9.0	9.7	1019 ± 24	cal AD 970–1040
SUERC-44007	SK028	–19.4	11.2	11.5	1199 ± 28	cal AD 720–940

SUERC-44110	SK029	–19.3	9.6	9.1	1338 ± 25	cal AD 640–770
SUERC-44111	SK033	–19.4	9.4	9.3	1322 ± 25	cal AD 650–770
SUERC-44112	SK038	–19.9	8.7	9.7	1125 ± 28	cal AD 770–1000
SUERC-44113	SK039	–20.1	8.5	10.7	1043 ± 26	cal AD 900–1030
SUERC-44114	SK043	–19.9	8.5	9.6	1180 ± 29	cal AD 730–950
SUERC-44115	SK045	–20.0	8.5	9.7	1215 ± 29	cal AD 690–890
SUERC-41982†	SK047	–20.2	8.5	9.8	1005 ± 24	cal AD 980–1150
SUERC-44119	SK048	–19.8	9.4	13.0	1194 ± 26	cal AD 720–940
SUERC-41983	SK051	–19.2	8.9	8.3	1389 ± 22	cal AD 610–670
SUERC-44120	SK052	–19.9	9.3	9.5	1151 ± 26	cal AD 770–970
SUERC-39955†	SK053	–20.1	7.7	10.3	1130 ± 30	cal AD 770–990
SUERC-44121	SK054	–19.5	10.3	11.0	1302 ± 26	cal AD 660–770
SUERC-44122†	SK056	–19.3	10.9	14.9	1184 ± 29	cal AD 720–950
SUERC-41984	SK057	–20.0	9.7	12.7	1083 ± 24	cal AD 890–1020
SUERC-41985	SK058	–19.0	9.8	7.5	1549 ± 24	cal AD 420–570
SUERC-39956†	SK061	–19.0	10.6	6.3	1560 ± 30	cal AD 420–570
SUERC-44123	SK065	–19.6	10.1	11.6	1027 ± 29	cal AD 900–1120
SUERC-39957†	SK066	–18.0	11.2	6.6	1705 ± 30	cal AD 250–410

SUERC-44124	SK075	–19.5	10.1	14.8	1144 ± 29	cal AD 770–980
SUERC-44125	SK076	–19.2	9.6	9.8	1324 ± 29	cal AD 650–770

Table 3: Radiocarbon ages and stable isotope values for modern Lake Mývatn freshwater fish bone collagen. Age ranges are based on measured ^{14}C ages following calibration with the IntCal13 atmospheric calibration curve and OxCal v.4.2. Calibrated dates are rounded outwards to 10 years. C:N ratios in italics are out with the 2.9 to 3.6 range indicating good quality bone collagen preservation (DeNiro, 1985), however are still included in this study as they passed the quality criteria set out by Ambrose (1990).

Reporting No.	**Species**	**Common name**	**Site**	**$\delta^{13}C$ [‰]**	**$\delta^{15}N$ [‰]**	**C:N ratio**	**Radiocarbon Age (BP)**	**Calibrated date (95% probability)**
SUERC-60328	*Salvelinus alpinus*	Arctic charr	Hamarshólar	–11.1	4.1	3.4	4628 ± 28	3520–3350 cal BC
SUERC-60329	*Salmo trutta*	Brown trout	Hamarshólar	–9.2	6.2	3.3	3795 ± 27	2340–2130 cal BC
SUERC-60330	*Salmo trutta*	Brown trout	Sviðinsey	–10.2	5.6	3.6	4275 ± 28	2930–2870 cal BC
SUERC-60331	*Salvelinus alpinus*	Arctic charr	Sviðinsey	–13.3	4.5	*3.8*	4820 ± 29	3660–3520 cal BC
SUERC-60335	*Salvelinus alpinus*	Arctic charr	Hrútey	–11.0	3.9	3.3	4513 ± 28	3360–3100 cal BC
SUERC-60336	*Salmo trutta*	Brown trout	Geitey	–8.2	5.6	3.3	5150 ± 26	4040–3810 cal BC
SUERC-60337	*Salmo trutta*	Brown trout	Strandabolir	–8.0	6.2	3.4	5329 ± 29	4260–4050 cal BC
SUERC-60338	*Salvelinus alpinus*	Arctic charr	Geitey	–9.6	8.0	3.4	4706 ± 26	3630–3370 cal BC
SUERC-60339	*Salvelinus alpinus*	Arctic charr	Grunnsvæði í Ytriflóa	–14.4	7.9	*3.8*	3802 ± 24	2340–2140 cal BC
SUERC-60340	*Salmo trutta*	Brown trout	Grunnsvæði í Ytriflóa	–11.9	6.6	3.4	4348 ± 27	3080–2900 cal BC
SUERC-60341	*Salvelinus alpinus*	Arctic charr	Djúp svæði í Ytriflóa	–11.3	6.6	3.3	4182 ± 27	2890–2670 cal BC

SUERC-60345	*Salmo trutta*	Brown trout	Djúp svæði í Ytriflóa	–11.1	7.0	3.3	4769 ± 27	3640–3380 cal BC

Table 4: Freshwater reservoir effect - corrected radiocarbon ages with errors at 1Ãand Bayesian modelled date ranges. Modelled dates have been rounded outwards to 5 years.

Reporting No.	**Dietary Model 1**			**Dietary Model 2**		
	$^{14}C_{corr}$ (BP)	**Modelled date (no tephra)**	**Modelled date (with tephra)**	**$^{14}C_{corr}$ (BP)**	**Modelled date (no tephra)**	**Modelled date (with tephra)**
		(95% probability)			**(95% probability)**	
SUERC-44824	865 ± 198	*cal AD 1125–1280*	*cal AD 1115–1280*	924 ± 180	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-43991	994 ± 218	*cal AD 1120–1275*	*cal AD 1110–1275*	1102 ± 167	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-43992	843 ± 186	*cal AD 1130–1280*	*cal AD 1115–1280*	901 ± 162	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-41973	881 ± 273	*cal AD 1125–1280*	*cal AD 1115–1280*	1046 ± 239	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-43993	942 ± 199	*cal AD 1125–1275*	*cal AD 1110–1280*	1039 ± 167	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-43994	937 ± 202	*cal AD 1125–1280*	*cal AD 1115–1280*	1048 ± 139	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-41974	976 ± 161	*cal AD 1120–1275*	*cal AD 1110–1275*	1033 ± 134	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-39947	875 ± 153	*cal AD 1130–1280*	*cal AD 1125–1280*	948 ± 106	*cal AD 1065–1250*	*cal AD 1065–1255*
SUERC-43995	873 ± 204	*cal AD 1125–1280*	*cal AD 1115–1280*	989 ± 147	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-39951	943 ± 174	*cal AD 1125–1275*	*cal AD 1115–1280*	1015 ± 139	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-43996	852 ± 192	*cal AD 1125–1280*	*cal AD 1120–1280*	945 ± 140	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-41975	884 ± 173	*cal AD 1125–1275*	*cal AD 1115–1280*	889 ± 177	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-43997	821 ± 188	*cal AD 1130–1280*	*cal AD 1120–1280*	921 ± 135	*cal AD 1060–1245*	*cal AD 1055–1250*

SUERC-44001	987 ± 162	*cal AD 1123–1275*	*cal AD 1110–1275*	1045 ± 134	*cal AD 1060–1240*	*cal AD 1055–1240*
SUERC-39952	745 ± 284	*cal AD 1125–1280*	*cal AD 1115–1280*	921 ± 321	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-39953	890 ± 174	*cal AD 1125–1280*	*cal AD 1115–1280*	966 ± 135	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-39954	904 ± 245	*cal AD 1125–1280*	*cal AD 1110–1280*	993 ± 226	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44002	868 ± 254	*cal AD 1125–1280*	*cal AD 1115–1280*	1014 ± 246	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44003	809 ± 270	*cal AD 1125–1280*	*cal AD 1115–1280*	943 ± 276	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-41976	819 ± 202	*cal AD 1125–1280*	*cal AD 1120–1280*	912 ± 171	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-41977	901 ± 188	*cal AD 1125–1275*	*cal AD 1115–1280*	970 ± 159	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44004	846 ± 179	*cal AD 1130–1280*	*cal AD 1115–1280*	893 ± 156	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44005	938 ± 204	*cal AD 1125–1280*	*cal AD 1115–1280*	1050 ± 139	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-44006	879 ± 178	*cal AD 1125–1280*	*cal AD 1115–1280*	968 ± 128	*cal AD 1060–1245*	*cal AD 1060–1245*
SUERC-41981	737 ± 193	*cal AD 1130–1280*	*cal AD 1120–1280*	792 ± 177	*cal AD 1060–1245*	*cal AD 1060–1250*
SUERC-44007	934 ± 197	*cal AD 1125–1280*	*cal AD 1115–1280*	1038 ± 137	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-44110	883 ± 247	*cal AD 1125–1280*	*cal AD 1115–1280*	1002 ± 228	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44111	896 ± 242	*cal AD 1125–1280*	*cal AD 1110–1280*	1006 ± 223	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44112	802 ± 212	*cal AD 1125–1280*	*cal AD 1115–1280*	851 ± 200	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44113	784 ± 180	*cal AD 1130–1280*	*cal AD 1120–1280*	807 ± 183	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44114	861 ± 212	*cal AD 1125–1280*	*cal AD 1115–1280*	900 ± 197	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44115	916 ± 199	*cal AD 1120–1275*	*cal AD 1110–1280*	950 ± 196	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-41982	750 ± 178	*cal AD 1130–1280*	*cal AD 1125–1280*	769 ± 181	*cal AD 1060–1250*	*cal AD 1060–1250*
SUERC-44119	960 ± 174	*cal AD 1120–1275*	*cal AD 1110–1280*	1031 ± 138	*cal AD 1060–1240*	*cal AD 1055–1245*

SUERC-41983	860 ± 250	*cal AD 1125–1280*	*cal AD 1110–1280*	952 ± 265	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44120	823 ± 208	*cal AD 1125–1280*	*cal AD 1115–1280*	888 ± 198	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-39955	869 ± 185	*cal AD 1125–1280*	*cal AD 1110–1280*	881 ± 185	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-44121	991 ± 206	*cal AD 1120–1275*	*cal AD 1110–1280*	1109 ± 164	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-44122	1017 ± 147	*cal AD 1120–1275*	*cal AD 1110–1275*	1072 ± 106	*cal AD 1060–1240*	*cal AD 1055–1240*
SUERC-41984	867 ± 165	*cal AD 1130–1275*	*cal AD 1120–1280*	932 ± 132	*cal AD 1060–1245*	*cal AD 1055–1250*
SUERC-41985	945 ± 270	*cal AD 1125–1275*	*cal AD 1110–1280*	1068 ± 268	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-39956	929 ± 276	*cal AD 1125–1280*	*cal AD 1110–1280*	1101 ± 269	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44123	746 ± 197	*cal AD 1130–1280*	*cal AD 1125–1280*	853 ± 150	*cal AD 1060–1245*	*cal AD 1060–1250*
SUERC-39957	750 ± 299	*cal AD 1125–1280*	*cal AD 1120–1280*	1068 ± 295	*cal AD 1060–1245*	*cal AD 1055–1245*
SUERC-44124	952 ± 158	*cal AD 1125–1275*	*cal AD 1115–1275*	1013 ± 121	*cal AD 1060–1240*	*cal AD 1055–1245*
SUERC-44125	875 ± 246	*cal AD 1125–1280*	*cal AD 1115–1280*	1027 ± 211	*cal AD 1060–1245*	*cal AD 1055–1245*

Figure Captions

Figure 1: Lake Mývatn and the archaeological site of Hofstaðir in north-east Iceland. Arctic charr and brown trout sampling sites: 1. Hamarshólar 2. Sviðinsey 3. Hrútey 4. Geitey 5. Strandabolir 6. Grunnsvæði í Ytriflóa 7. Djúp svæði í Ytriflóa.

Figure 2: (A) Uniform prior distribution model showing 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 has been used to calculate the percentage of freshwater and marine protein in their diet. The full model is shown in Fig. S1 in Supplementary Material. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model. (B) The span of activity associated with the use of the cemetery at Hofstaðir, which is derived from the chronological model shown in Fig. 2A.

Figure 3: (A) Uniform prior distribution model showing 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 2 has been used to calculate the percentage of freshwater and marine protein in their diet. The full model is shown in Fig. S3 in Supplementary Material. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model. (B) The span of activity associated with the use of the cemetery at Hofstaðir, which is derived from the chronological model shown in Fig. 3A.

Figure 4: (A) Uniform prior distribution model for 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 and (B) FRUITS Dietary Model 2 have been used to calculate the percentage of freshwater and marine protein in their diet. The full models are shown in Figs. S2 and S4 in Supplementary Material. The radiocarbon ages used to construct these Bayesian models have been corrected for a freshwater reservoir effect. The start and end boundaries in both models are constrained by the Veiðivötn tephra of AD 933 and the Hekla tephra of AD 1300.

Figure 5: Summary graphic of start and end probability density estimates for FRUITS Dietary Models 1 and 2, both with and without tephra priors. The probabilities are derived from Figs. 2, 3 and 4, with full models shown in Figs. S1-S4 in Supplementary Material.

Supplementary Material

Table S1: Calculated percentages, using FRUITS, of terrestrial, marine and freshwater dietary protein in human bone collagen from 46 individuals excavated from Hofstaðir cemetery. *The percentage of marine protein in the diet was previously calculated by linear interpolation using end-point values of –13.3‰ (100% marine) and –20.7‰ (100% terrestrial) (Cook et al., 2015), and are included for comparison of the two methods.

Reporting No.	% Marine (±10%)*	Dietary Model 1			Dietary Model 2		
		% Terrestrial	% Marine	% Freshwater	% Terrestrial	% Marine	% Freshwater
SUERC-44824	14	86 ± 5	8 ± 5	6 ± 4	78 ± 6	17 ± 7	5 ± 4
SUERC-43991	17	82 ± 6	11 ± 6	7 ± 5	74 ± 7	22 ± 7	5 ± 4
SUERC-43992	11	86 ± 5	8 ± 5	6 ± 4	80 ± 6	16 ± 7	4 ± 4
SUERC-41973	24	78 ± 6	11 ± 6	11 ± 6	71 ± 6	22 ± 8	8 ± 5
SUERC-43993	14	83 ± 6	11 ± 6	6 ± 4	75 ± 7	20 ± 8	4 ± 4
SUERC-43994	21	77 ± 6	17 ± 7	6 ± 4	68 ± 7	29 ± 8	4 ± 3
SUERC-41974	13	84 ± 6	11 ± 6	5 ± 4	76 ± 7	20 ± 7	3 ± 3
SUERC-39947	28	67 ± 6	29 ± 7	4 ± 3	56 ± 7	41 ± 7	2 ± 2
SUERC-43995	25	76 ± 7	17 ± 8	6 ± 4	67 ± 7	29 ± 7	4 ± 3
SUERC-39951	12	83 ± 6	12 ± 6	5 ± 4	75 ± 6	22 ± 7	3 ± 3
SUERC-43996	19	80 ± 6	15 ± 7	6 ± 4	70 ± 7	26 ± 7	4 ± 3
SUERC-41975	8	90 ± 4	4 ± 3	5 ± 4	85 ± 6	9 ± 6	5 ± 4
SUERC-43997	13	82 ± 6	12 ± 6	6 ± 4	74 ± 7	22 ± 7	3 ± 3
SUERC-44001	10	85 ± 5	10 ± 6	5 ± 4	77 ± 7	19 ± 8	3 ± 3

SUERC-39952	46	65 ± 6	7 ± 5	28 ± 6	59 ± 6	17 ± 8	25 ± 7
SUERC-39953	11	84 ± 6	11 ± 6	5 ± 4	77 ± 7	20 ± 7	3 ± 3
SUERC-39954	17	82 ± 6	8 ± 5	10 ± 5	77 ± 7	15 ± 8	8 ± 5
SUERC-44002	21	80 ± 6	8 ± 5	12 ± 6	75 ± 6	17 ± 7	9 ± 5
SUERC-44003	25	79 ± 6	6 ± 5	14 ± 6	74 ± 6	15 ± 8	11 ± 6
SUERC-41976	11	84 ± 6	9 ± 6	7 ± 4	78 ± 6	17 ± 7	5 ± 4
SUERC-41977	16	85 ± 5	9 ± 5	6 ± 4	77 ± 6	19 ± 7	4 ± 3
SUERC-44004	8	87 ± 5	8 ± 5	5 ± 4	81 ± 6	14 ± 7	4 ± 3
SUERC-44005	21	78 ± 6	16 ± 7	6 ± 4	68 ± 6	28 ± 7	4 ± 3
SUERC-44006	15	81 ± 6	14 ± 7	5 ± 4	71 ± 7	26 ± 8	3 ± 3
SUERC-41981	7	87 ± 5	6 ± 4	6 ± 4	83 ± 6	12 ± 7	5 ± 4
SUERC-44007	18	77 ± 6	17 ± 7	6 ± 4	68 ± 5	29 ± 7	4 ± 3
SUERC-44110	19	82 ± 6	8 ± 6	10 ± 5	75 ± 7	17 ± 8	7 ± 5
SUERC-44111	17	82 ± 6	8 ± 5	9 ± 5	76 ± 7	17 ± 8	7 ± 5
SUERC-44112	11	87 ± 5	6 ± 4	7 ± 5	82 ± 6	12 ± 7	6 ± 4
SUERC-44113	9	88 ± 5	6 ± 4	6 ± 4	82 ± 6	12 ± 6	5 ± 4
SUERC-44114	11	87 ± 5	6 ± 4	7 ± 5	83 ± 6	11 ± 6	6 ± 4
SUERC-44115	10	88 ± 5	5 ± 4	7 ± 4	83 ± 6	11 ± 6	6 ± 4
SUERC-41982	7	89 ± 5	5 ± 4	6 ± 4	84 ± 6	11 ± 6	5 ± 4
SUERC-44119	12	85 ± 6	10 ± 6	5 ± 4	76 ± 6	20 ± 7	4 ± 3
SUERC-41983	20	82 ± 5	7 ± 5	12 ± 5	77 ± 6	14 ± 7	10 ± 6

SUERC-44120	11	86 ± 5	7 ± 5	7 ± 5	80 ± 6	14 ± 7	6 ± 4
SUERC-39955	9	89 ± 5	5 ± 4	6 ± 4	85 ± 6	9 ± 6	5 ± 4
SUERC-44121	17	81 ± 6	12 ± 6	7 ± 5	73 ± 7	23 ± 7	4 ± 4
SUERC-44122	19	77 ± 7	19 ± 8	4 ± 3	66 ± 7	32 ± 7	2 ± 2
SUERC-41984	10	85 ± 6	10 ± 6	5 ± 4	77 ± 7	20 ± 7	3 ± 3
SUERC-41985	24	79 ± 6	7 ± 5	13 ± 6	73 ± 7	16 ± 7	11 ± 6
SUERC-39956	23	78 ± 6	8 ± 6	14 ± 6	72 ± 7	18 ± 8	10 ± 6
SUERC-44123	15	82 ± 6	12 ± 6	6 ± 4	74 ± 7	22 ± 7	4 ± 3
SUERC-39957	36	68 ± 6	11 ± 6	21 ± 7	62 ± 7	24 ± 9	14 ± 6
SUERC-44124	16	81 ± 6	15 ± 7	4 ± 3	71 ± 7	26 ± 7	3 ± 3
SUERC-44125	21	81 ± 6	9 ± 6	10 ± 5	73 ± 6	20 ± 7	7 ± 5

Table S2: Uncorrected and freshwater corrected radiocarbon ages and errors for Hofstaðir humans (quoted in years BP). FW_{corr} represents the radiocarbon correction for freshwater input in a person's diet and $FW_{corr/err}$ its associated error. $^{14}C_{corr}$ is the freshwater corrected radiocarbon age, which was determined by subtracting FW_{corr} from the original radiocarbon age (^{14}CA), and $^{14}C_{err/corr}$ is its associated error. Unmodelled calibrated dates are rounded outwards to 10 years.

			Dietary Model 1				**Dietary Model 2**			
Reporting No.	**Radiocarbon Age (^{14}CA) (BP)**	**Unmodelled Calibrated date (95% probability)**	**FW_{corr}**	**$FW_{err/corr}$**	**$^{14}C_{corr}$**	**$^{14}C_{err/corr}$**	**FW_{corr}**	**$FW_{err/corr}$**	**$^{14}C_{corr}$**	**$^{14}C_{err/corr}$**
SUERC-44824	1149 ± 35	cal AD 770–980	284	195	865	198	225	177	924	180
SUERC-43991	1309 ± 29	cal AD 650–770	312	216	997	218	207	164	1102	167
SUERC-43992	1097 ± 29	cal AD 880–1020	254	184	843	186	196	159	901	162
SUERC-41973	1395 ± 24	cal AD 600–670	514	272	881	273	349	238	1046	239
SUERC-43993	1232 ± 29	cal AD 680–890	290	197	942	199	193	164	1039	167
SUERC-43994	1212 ± 29	cal AD 690–890	275	200	937	202	164	136	1048	139
SUERC-41974	1183 ± 24	cal AD 770–950	207	159	976	161	150	131	1033	134
SUERC-39947	1060 ± 30	cal AD 890–1030	185	150	875	153	112	101	948	106
SUERC-43995	1163 ± 29	cal AD 770–970	290	202	873	204	174	144	989	147
SUERC-39951	1170 ± 30	cal AD 770–970	227	171	943	174	155	136	1015	139
SUERC-43996	1109 ± 29	cal AD 880–1020	257	190	852	192	164	137	945	140
SUERC-41975	1123 ± 24	cal AD 780–990	239	171	884	173	234	176	889	177
SUERC-43997	1075 ± 29	cal AD 890–1020	254	186	821	188	154	132	921	135
SUERC-44001	1196 ± 29	cal AD 720–940	209	159	987	162	151	131	1045	134

SUERC-39952	2030 ± 30	160 cal BC – cal AD 60	1285	282	745	284	1109	320	921	321
SUERC-39953	1120 ± 30	cal AD 770–1000	230	171	890	174	154	132	966	135
SUERC-39954	1340 ± 30	cal AD 640–770	436	243	904	245	347	224	993	226
SUERC-44002	1402 ± 30	cal AD 590–670	534	253	868	254	388	244	1014	246
SUERC-44003	1461 ± 29	cal AD 550–650	652	269	809	270	518	275	943	276
SUERC-41976	1117 ± 20	cal AD 890–980	298	201	819	202	205	170	912	171
SUERC-41977	1161 ± 24	cal AD 770–970	260	187	901	188	191	158	970	159
SUERC-44004	1089 ± 29	cal AD 890–1020	243	177	846	179	196	154	893	156
SUERC-44005	1218 ± 28	cal AD 690–890	280	202	938	204	168	136	1050	139
SUERC-44006	1111 ± 28	cal AD 870–1020	232	176	879	178	143	125	968	128
SUERC-41981	1019 ± 24	cal AD 970–1040	282	191	737	193	227	175	792	177
SUERC-44007	1199 ± 28	cal AD 720–940	265	195	934	197	161	134	1038	137
SUERC-44110	1338 ± 25	cal AD 640–770	455	246	883	247	336	227	1002	228
SUERC-44111	1322 ± 25	cal AD 650–770	426	240	896	242	316	222	1006	223
SUERC-44112	1125 ± 28	cal AD 770–1000	323	210	802	212	274	198	851	200
SUERC-44113	1043 ± 26	cal AD 900–1030	259	178	784	180	236	181	807	183
SUERC-44114	1180 ± 29	cal AD 730–950	319	210	861	212	280	195	900	197
SUERC-44115	1215 ± 29	cal AD 690–890	299	197	916	199	265	194	950	196
SUERC-41982	1005 ± 24	cal AD 980–1150	255	177	750	178	236	180	769	181
SUERC-44119	1194 ± 26	cal AD 720–940	234	172	960	174	163	136	1031	138
SUERC-41983	1389 ± 22	cal AD 610–670	529	249	860	250	437	264	952	265

SUERC-44120	1151 ± 26	cal AD 770–970	328	207	823	208	263	196	888	198
SUERC-39955	1130 ± 30	cal AD 770–990	261	183	869	185	249	183	881	185
SUERC-44121	1302 ± 26	cal AD 660–770	311	204	991	206	193	162	1109	164
SUERC-44122	1184 ± 29	cal AD 720–950	167	145	1017	147	112	102	1072	106
SUERC-41984	1083 ± 24	cal AD 890–1020	216	163	867	165	151	129	932	132
SUERC-41985	1549 ± 24	cal AD 420–570	604	269	945	270	481	267	1068	268
SUERC-39956	1560 ± 30	cal AD 420–570	631	274	929	276	459	268	1101	269
SUERC-44123	1027 ± 29	cal AD 900–1120	281	195	746	197	174	147	853	150
SUERC-39957	1705 ± 30	cal AD 250–410	955	297	750	299	637	294	1068	295
SUERC-44124	1144 ± 29	cal AD 770–980	192	155	952	158	131	118	1013	121
SUERC-44125	1324 ± 29	cal AD 650–770	449	244	875	246	297	209	1027	211

Figure S1: Uniform prior distribution model for 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 has been used to calculate the percentage of freshwater and marine protein in their diet. 9 individuals have been subset into Fig. 2A in the main text. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model.

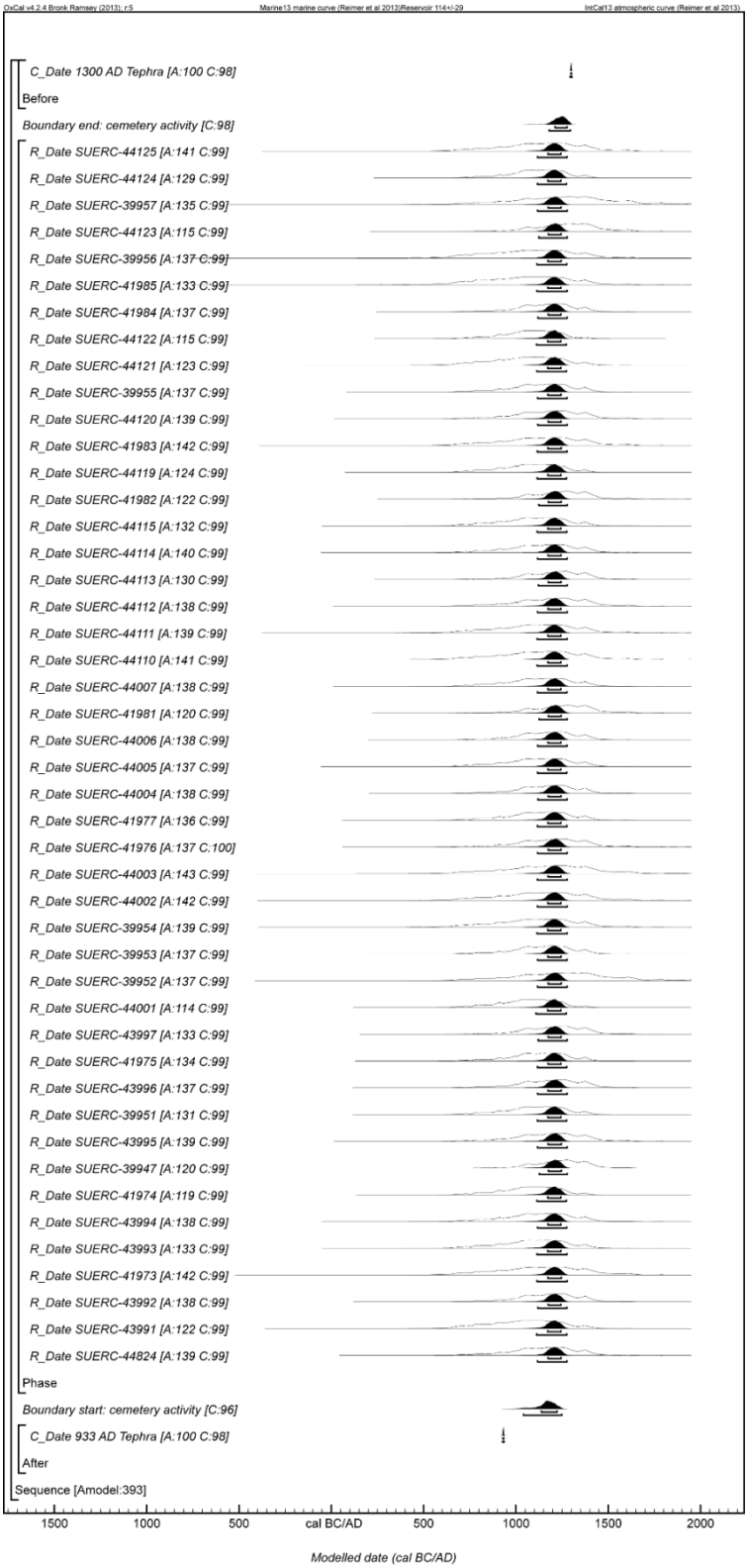

Figure S2: Uniform prior distribution model for 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 has been used to calculate the percentage of freshwater and marine protein in their diet. 9 individuals have been subset into Fig. 4A in the main text. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. The start and end boundaries are constrained by the Veiðivötn tephra of AD 933 and the Hekla tephra of AD 1300.

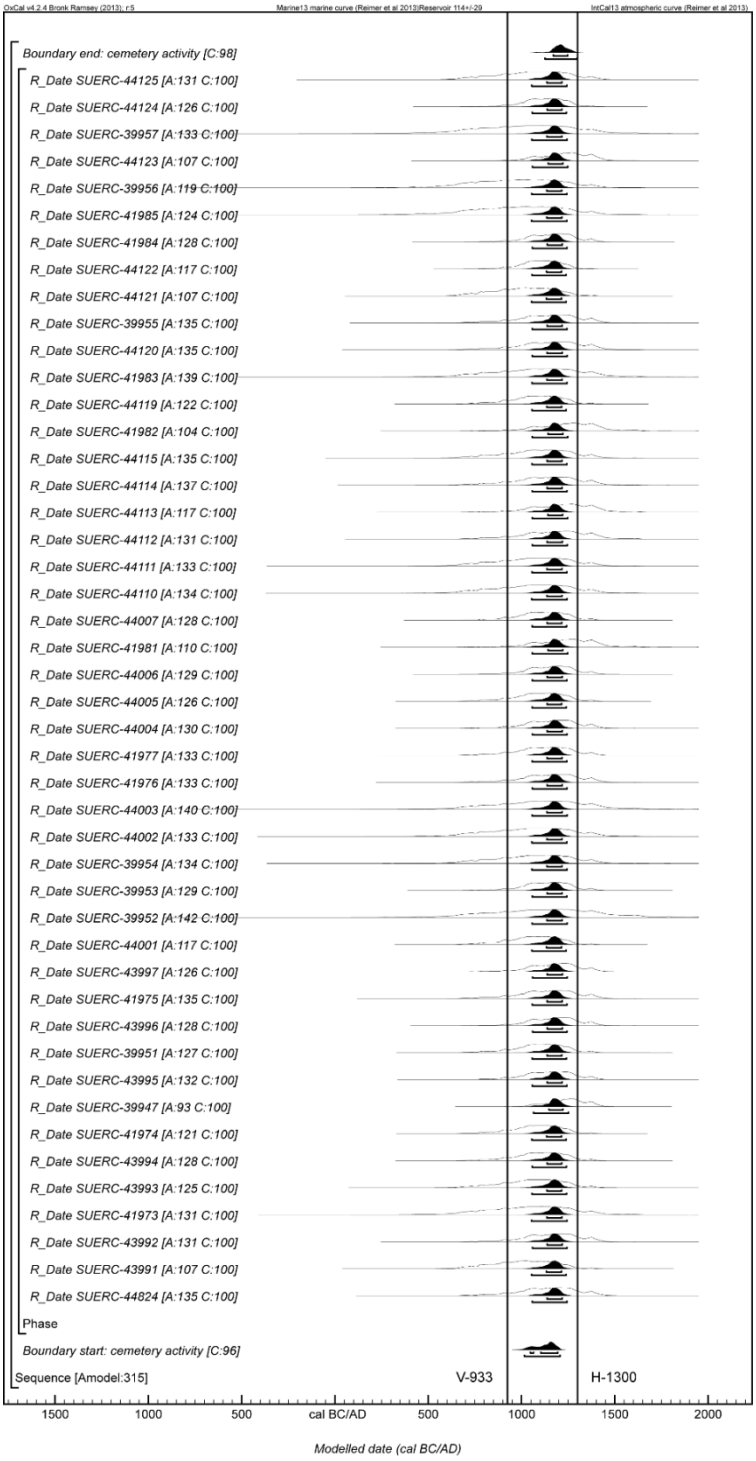

Figure S3: Uniform prior distribution model for 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 2 has been used to calculate the percentage of freshwater and marine protein in their diet. 9 individuals have been subset into Fig. 3A in the main text. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model.

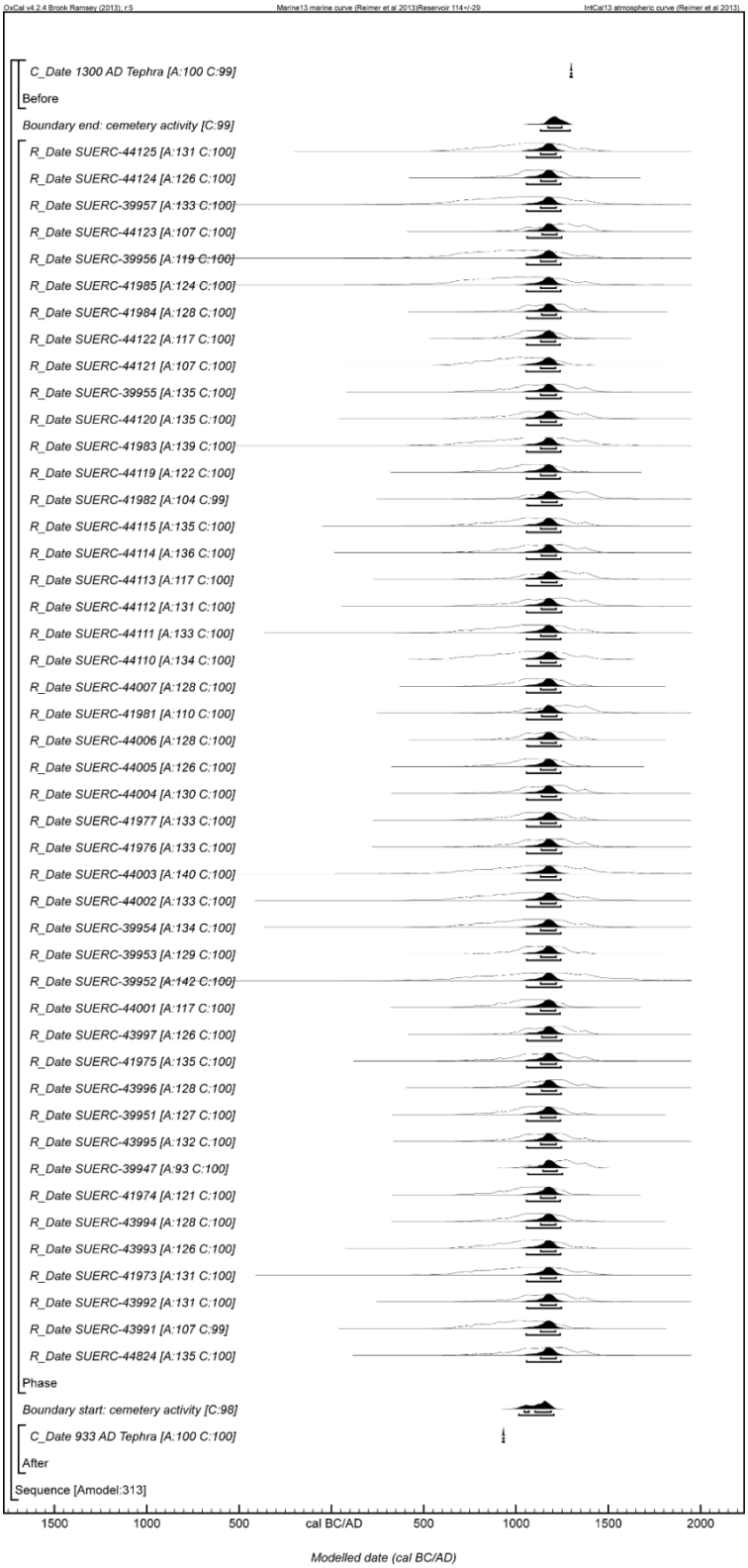

Figure S4: Uniform prior distribution model for 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 2 has been used to calculate the percentage of freshwater and marine protein in their diet. 9 individuals have been subset into Fig. 4B in the main text. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. The start and end boundaries are constrained by the Veiðivötn tephra of AD 933 and the Hekla tephra of AD 1300.

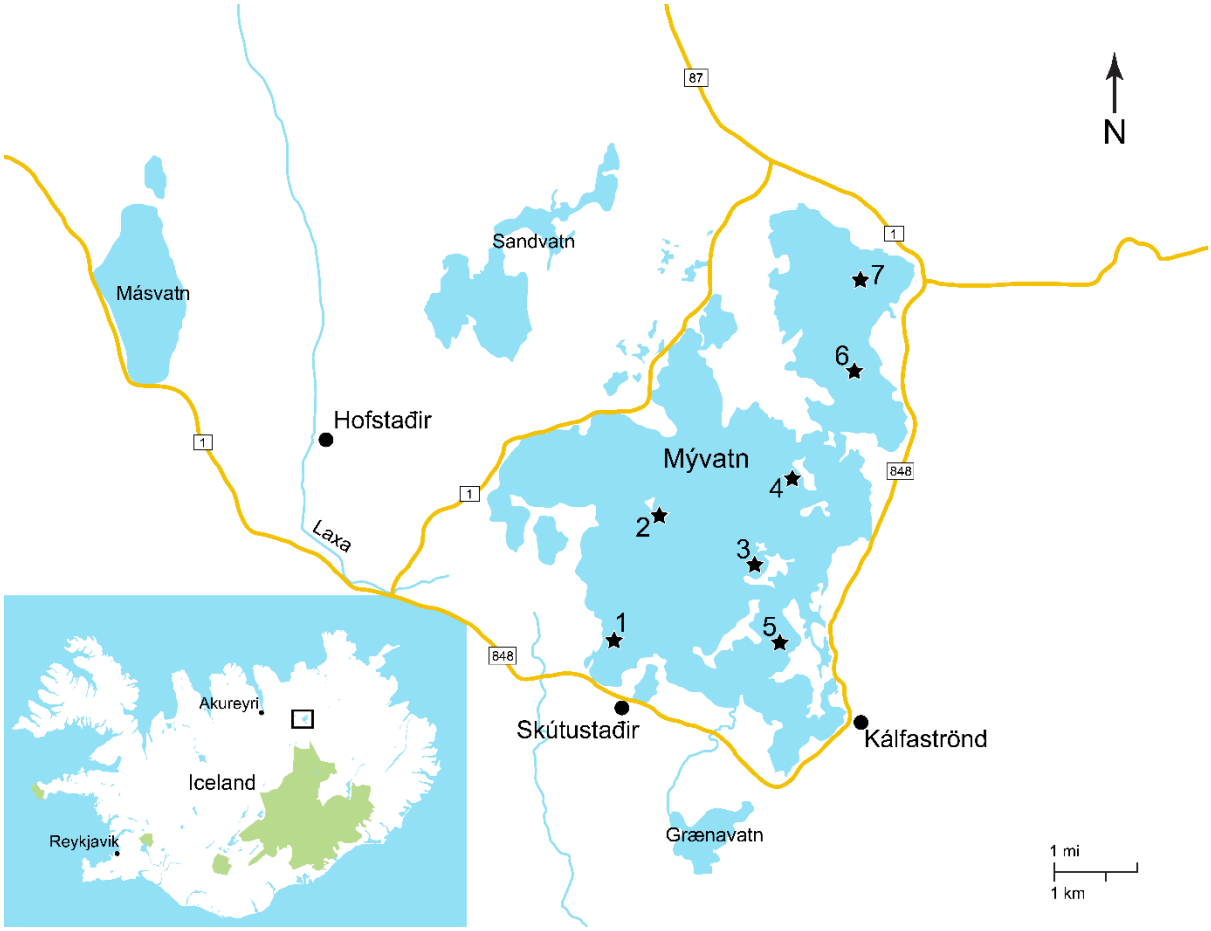

Figure 1: Lake Mývatn and the archaeological site of Hofstaðir in north-east Iceland. Arctic charr and brown trout sampling sites: 1. Hamarshólar 2. Sviðinsey 3. Hrútey 4. Geitey 5. Strandabolir 6. Grunnsvæði í Ytriflóa 7. Djúp svæði í Ytriflóa.

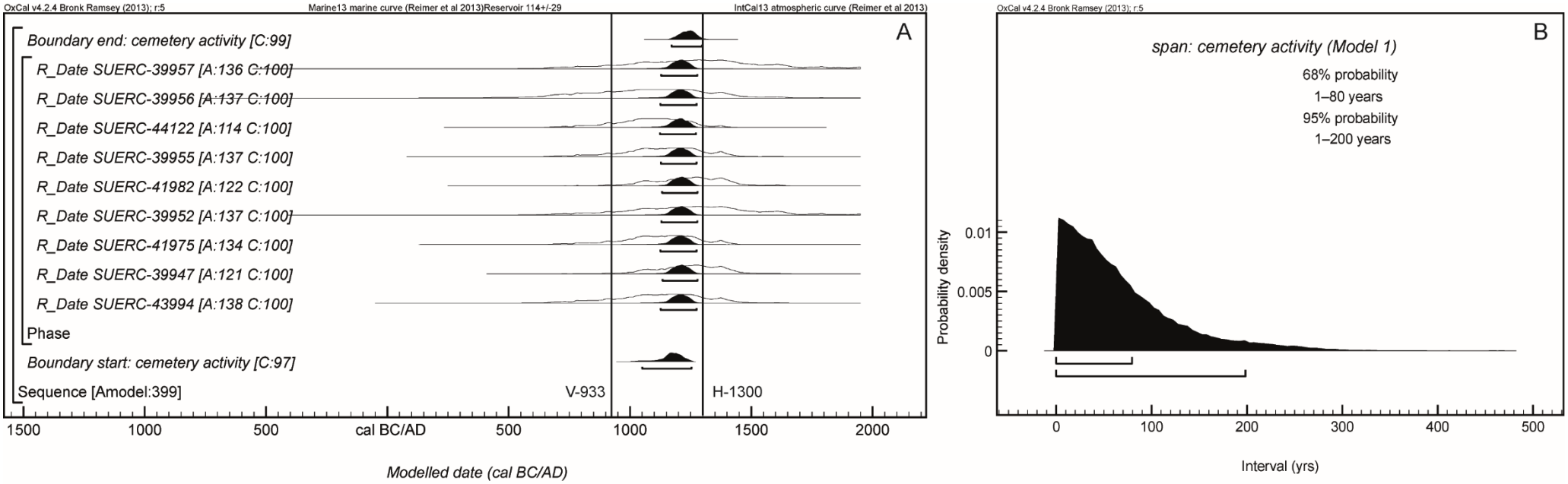

Figure 2: (A) Uniform prior distribution model showing 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 has been used to calculate the percentage of freshwater and marine protein in their diet. The full model is shown in Fig. S1 in Supplemental Material. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model. (B) The span of activity associated with the use of the cemetery at Hofstaðir, which is derived from the chronological model shown in Fig. 2A.

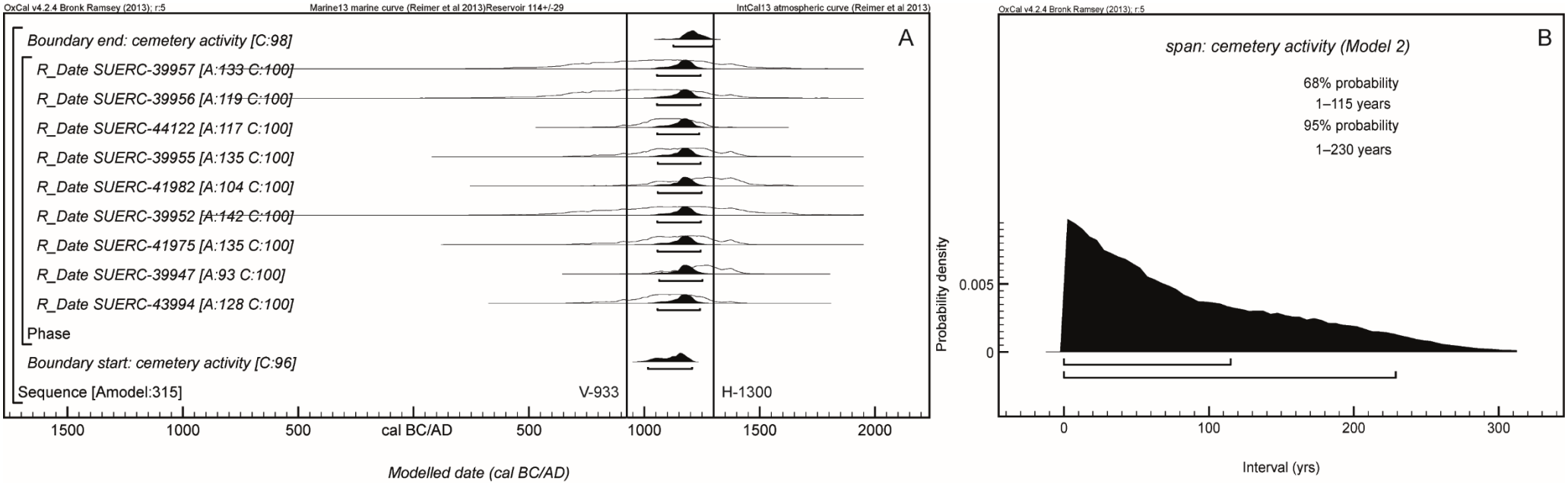

Figure 3: (A) Uniform prior distribution model showing 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 2 has been used to calculate the percentage of freshwater and marine protein in their diet. The full model is shown in Fig. S3 in Supplemental Material. The radiocarbon ages used to construct this Bayesian model have been corrected for a freshwater reservoir effect. Lines marked V-933 and H-1300 illustrate when the Veiðivötn (AD 933) and Hekla (AD 1300) volcanoes erupted, but are not constraining the model. (B) The span of activity associated with the use of the cemetery at Hofstaðir, which is derived from the chronological model shown in Fig. 3A.

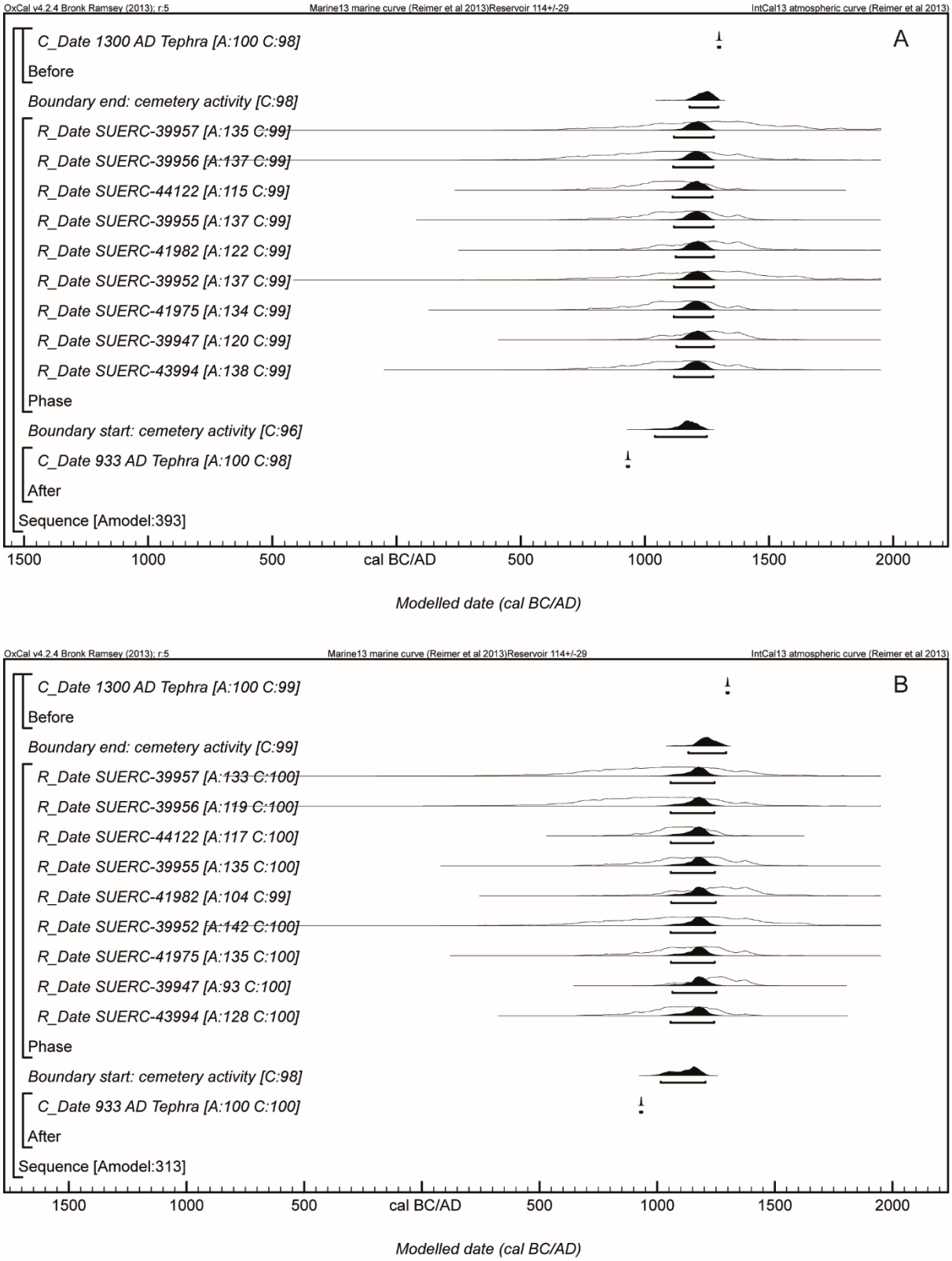

Figure 4: (A) Uniform prior distribution model for 9 of 46 individuals at Hofstaðir cemetery when FRUITS Dietary Model 1 and (B) FRUITS Dietary Model 2 have been used to calculate the percentage of freshwater and marine protein in their diet. The full models are shown in Figs. S2 and S4 in Supplemental Material. The radiocarbon ages used to construct these Bayesian models have been corrected for a freshwater reservoir effect. The start and end boundaries in both models are constrained by the Veiðivötn tephra of AD 933 and the Hekla tephra of AD 1300.

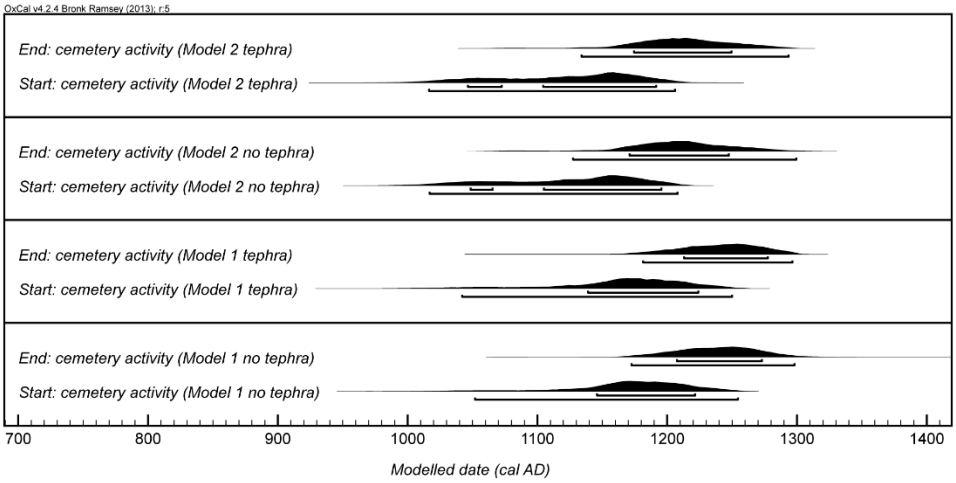

Figure 5: Summary graphic of start and end probability density estimates for FRUITS Dietary Models 1 and 2, both with and without tephra priors. The probabilities are derived from Figs. 2, 3 and 4, with full models shown in Figs. S1-S4 in Supplemental Material.