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FRESHWATER RESERVOIR OFFSETS INVESTIGATED THROUGH PAIRED HUMAN-FAUNAL ^{14}C DATING AND STABLE CARBON AND NITROGEN ISOTOPE ANALYSIS AT LAKE BAIKAL, SIBERIA

Rick J Schulting[1,2] • Christopher Bronk Ramsey[1] • Vladimir I Bazaliiskii[3] • Olga I Goriunova[3] • Andrzej Weber[4]

ABSTRACT. Thirty-three paired accelerator mass spectrometry (AMS) radiocarbon dates on human and terrestrial faunal remains from the same Neolithic and Early Bronze Age graves are used to develop a correction for the freshwater reservoir effect (FRE) at Lake Baikal, Siberia. Excluding two outliers, stable nitrogen isotope (δ^{15}N) values show a positive correlation ($r^2 = 0.672$, $p < 0.000$) with offsets in ^{14}C yr between paired human and fauna determinations. The highest offset observed in our data set is 622 yr, which is close to the value of ~700 yr suggested for endemic seals in the lake. For each per mil increase in δ^{15}N, the offset increases by 77 ± 10 yr in the overall data set. However, there are indications that different regression models apply in each of two microregions of Cis-Baikal. In the first, sites on the southwest shore of the lake and along the Angara River show a strong positive correlation between δ^{15}N values and offsets in ^{14}C yr ($r^2 = 0.814$, $p < 0.000$). In the other, the Little Sea, both δ^{13}C and δ^{15}N values make significant contributions to the model (adjusted $r^2 = 0.878$; δ^{13}C $p < 0.001$; δ^{15}N $p < 0.000$). This can be related to the complex ^{13}C ecology of the lake, which displays one of the widest ranges of δ^{13}C values known for any natural ecosystem. The results will be important in terms of refining the culture-history of the region, as well as exploring the dynamic interactions of hunter-gatherer communities both synchronically and diachronically.

INTRODUCTION

While the marine reservoir effect is already well known, a similar effect on radiocarbon dates is being increasingly documented in freshwater contexts from a number of locations around the world, including Viking Age Iceland (Ascough et al. 2010), the Iron Gates region of the Lower Danube (Cook et al. 2001), the Dnieper Rapids in the Ukraine (Lillie et al. 2009), Ostorf in northern Germany (Olsen et al. 2010), and Minino and Klin Yar in western Russia (Higham et al. 2010; Wood et al. 2013). Additionally, a freshwater reservoir effect (FRE) has been recently identified in archaeological seal remains from Lake Baikal in southern Siberia (Nomokonova et al. 2013). This has important implications for understanding the prehistory of the Cis-Baikal region, which, due to the wealth of its mortuary and skeletal evidence, provides one of the richest resources for investigating aspects of Holocene hunter-gatherer behavior in all of Eurasia (Weber and Bettinger 2010). This study uses paired accelerator mass spectrometry (AMS) ^{14}C dating of human bone and terrestrial animal teeth from the same graves in order to quantify the extent to which old carbon from the lake is affecting human ^{14}C determinations. A total of 83 ^{14}C dates on human and faunal remains have been obtained for 33 graves from the Cis-Baikal cemeteries of Lokomotiv, Shamanka II, Ust'-Ida, Kurma XI, and Khuzhir-Nuge XIV (Figure 1). These sites differ in their chronology and their geographical location, both factors relevant in terms of the subsistence economy of the populations using the sites for burial. Extensive stable carbon and nitrogen isotope analyses have shown that Neolithic and Early Bronze Age humans here consumed temporally and spatially variable, but typically substantial amounts of fish and seals from Lake Baikal and the rivers around it (Lam 1994; Katzenberg and Weber 1999; Weber et al. 2002, 2011; Katzenberg et al. 2009, 2010, 2012; Weber and Goriunova 2013). It is thus expected that there should be a relationship between the human stable isotope values and the offset in ^{14}C yr between the human and animal determinations from the same grave. The investigation of this relationship is the focus of this paper, with the goal of presenting a regression equation to "correct" for the FRE on the large number of human bone dates already available from Cis-Baikal (Weber et al. 2010).

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[1] Research Laboratory for Archaeology and the History of Art, Dyson Perrins Building, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom.

[2] Corresponding author email: rick.schulting@arch.ox.ac.uk.

[3] Department of Archaeology and Ethnography, Irkutsk State University, Karl Marx Street 1, Irkutsk 664003, Russia.

[4] Department of Anthropology, 13-15 H.M. Tory Building, University of Alberta, Edmonton, Alberta T6G 2H4, Canada.

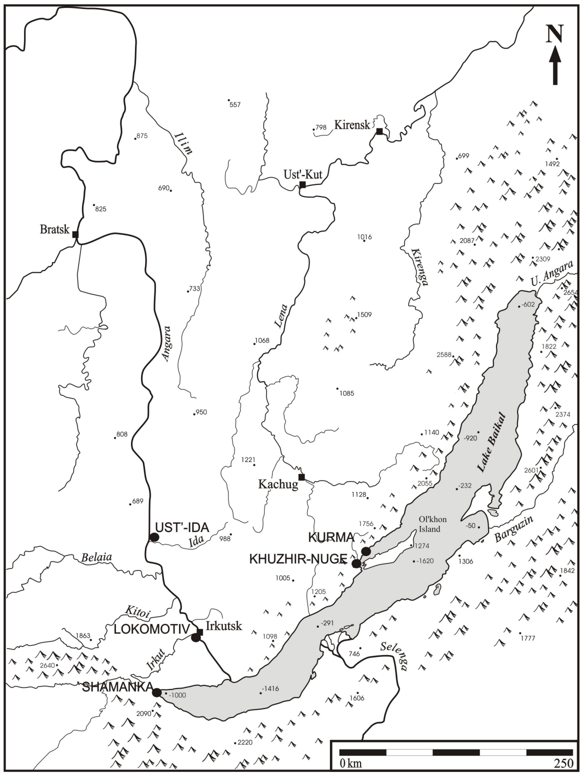

Figure 1 Map of Cis-Baikal showing locations of cemeteries mentioned in the text.

LAKE BAIKAL

Lake Baikal is the world's largest, deepest, and oldest freshwater lake, giving it a unique ecosystem with a high proportion of endemic species (Kozhov 1972). There has been, therefore, considerable interest in the lake, including hydrological, geochemical, and paleoenvironmental investigations and, of most direct relevance here, the elucidation of its carbon flows and food webs using stable carbon and nitrogen isotopes (Kiyashko et al. 1998; Katzenberg and Weber 1999; Yoshii 1999; Yoshii et al. 1999; Ogawa et al. 2000; Weber et al. 2011). These studies have found the lake's isotopic ecology to be complex, with an unsurpassed range of δ^{13}C values (France 1995), the basis of which lies in the non-overlapping ranges of the two primary producers: phytoplankton and attached green algae (periphyton). The contribution of terrestrial carbon from runoff and riverine input to Lake Baikal constitutes a minor proportion of the lake's total carbon reservoir, reported as 10% or less (Weiss et al. 1991). Phytoplankton occur in the water column throughout the lake, with average δ^{13}C values of –30.5 ± 2.2‰, while attached green algae occur only in the shallow, inshore benthic zone (<75–100 m depth), and average –9.0 ± 2.5‰ (Yoshii 1999; Kiyashko et al. 1998). This provides a range of 21.5‰, akin to that seen between C_3 and C_4 plants in terrestrial systems. The pelagic food web is based on phytoplankton, and so the δ^{13}C values of consumers in this zone, including the endemic Baikal seal (*Phoca sibirica*), are relatively homogeneous, with bone collagen values of about –22‰ [the elevation above the primary producer average of –30.5‰ reflects both diet-collagen fractionation and trophic level enrichment (Weber et al. 2002; Katzenberg et al. 2012)]. The values for those species feeding at least partly in the inshore benthic zone, in contrast, are highly variable, with some exhibiting extremely elevated values up to about –10‰, while others are depleted (Katzenberg and Weber 1999; Weber et al. 2011). The end result of this is that, unlike most marine systems, $\delta^{13}C$ values on their own cannot be used as a sufficient proxy for the degree of human consumption of Baikal fish and seals.

Alkalinity has been found to be a significant predictor of reservoir ages in lakes (Keaveney and Reimer 2012). This, however, is not relevant to the Baikal situation, as there is negligible carbonate input from the lake's catchment (Prokopenko et al. 1999). Because the rivers feeding into Lake Baikal do not flow over carbonate bedrock, the general expectation has been that there is no significant input of old carbon, and that therefore the lake's waters should not exhibit a reservoir age beyond that seen in water residence time. However, Prokopenko et al. (1999:244) noted a systematic offset in ^{14}C determinations on sediment cores from the lake bottom during a paleoenvironmental investigation of the last glacial-interglacial transition, with dates being older than expected (see also Colman et al. 1996). They were unable to offer an explanation for this, and suggested that further work was required. Possibilities include the introduction of old CO_2 via the influx of glacial meltwater (Osipov and Khlystov 2010), dead carbon from methane hydrates (Prokopenko and Williams 2004), and the residence time of water within the lake itself.

Numerous studies have indicated that the surface and deep waters of Lake Baikal undergo rapid mixing, on the order of 1 to 2 decades (Falkner et al. 1991, 1997; Hohmann et al. 1997; Peeters et al. 1997). Thus, there would appear to be no old water reservoir at the bottom of the lake that could bring ^{14}C-depleted carbon to the surface via upwelling. Correspondingly, it might be expected that any ^{14}C deficit would be similar throughout the lake, though this would benefit from further research. Residence time for water in Lake Baikal as a whole has been estimated as 377 yr, based on calculations of the pre-dam river inflow and outflow, combined with the lake's water volume estimated at 23,000 km^3 (Afanas'ev 1960:Table 55; see also Kozhov 1963:28). However, as discussed below, the value of 377 yr is approximately half the reservoir age indicated by archaeological dating programs comparing lake and terrestrial organisms. In fact, the discrepancy is far greater than indicated by this comparison, since water residence time can be considered as the equivalent of bone turnover rates in stable isotope studies, so that, for example, half the water in the lake will have been replaced approximately every 190 yr. In other words, water residency times do not provide a straightforward "age" for the water, and hence not for the dissolved CO_2 it contains. In any case, we do not aim to identify the source of the reservoir age here, but rather to quantify its effects on the ^{14}C content of humans consuming varying amounts and kinds of aquatic resources from Lake Baikal.

MATERIALS AND METHODS

A total of 33 paired human-animal samples from the same graves were selected for ^{14}C dating and stable carbon and nitrogen isotope analysis, from the Early Neolithic cemeteries of Lokomotiv/Lokomotiv-Raisovet and Shamanka II, the Late Neolithic component of Ust'-Ida, and the Early Bronze Age (EBA) cemeteries of Kurma XI and Khuzhir-Nuge XIV (Table 1). Lokomotiv-Raisovet is a cluster of graves within the larger Lokomotiv cemetery and so constitutes part of the same site. The two EBA sites are located in the Little Sea area of Lake Baikal, and are combined under this heading in the analysis. The terrestrial counterparts to the dated humans from the same graves are in all cases supplied by perforated or unmodified terrestrial animal teeth (Figure 2). These formed part of the grave offerings, and so can be directly associated with the burials. It is assumed that these were not kept over significant periods of time as heirlooms. Any such curation that did occur will contribute to the "noise" in the regression model. In the case of the two Early Neolithic cemeteries, the unmodified teeth are marmot (*Marmota* sp.) incisors (thought to have been attached to head-gear and clothing), while for all the other cemeteries the teeth are perforated red deer (*Cervus elaphus*) canines.

Figure 2 Grave 13 from Kurma XI, with red deer incisors in chest area.

Table 1 Cis-Baikal cemeteries providing the paired human-faunal dates used in this study. One grave contributed two paired dates, four graves contain two dated individuals, and one contained three, accounting for the difference in the number of human and animal samples.

Site	Location	Period	*n* graves	*n* human	*n* animal
Lokomotiv	Angara	Early Neolithic	5	9	5
Shamanka	SW Baikal	Early Neolithic	5	9	7
Ust'-Ida	Angara	Late Neolithic	7	10	7
Kurma XI	Little Sea	Early Bronze Age	8	9	9
Khuzhir-Nuge XIV	Little Sea	Early Bronze Age	8	10	8
		Total	**33**	**47**	**36**

A potential complication arises in that some of the individuals are infants and young children, and so may be subject to elevated δ^{15}N values as a result of the nursing effect (Schurr 1998), rather than the consumption of high-trophic-level protein from Lake Baikal and/or the rivers of the region. In a recent detailed isotopic study of weaning practices, Waters-Rist et al. (2011) found that weaning in the Early Neolithic was not complete until 3.5–4 yr of age, while at Late Neolithic Ust'-Ida, weaning seems to have been completed by age 3. The youngest individual from the Early Neolithic Lokomotiv site is aged 4–7 yr, and is therefore likely to have been fully weaned, and to retain little residual nursing influence on its δ^{15}N signal. This is confirmed by this individual's δ^{15}N value of 14.5‰, which is slightly lower than the average of 14.8‰ for the eight other individuals from the site included in this study, though slightly higher than the average for all adult individuals from the cemetery as a whole (14.1 ± 0.7‰; Weber et al. 2011). Only the youngest individual in the current study, from Ust'-Ida (UID 1988.017), aged 2–4, is sufficiently young to be subject to a nursing effect, borne out by its high δ^{15}N value of 15.5‰, well above the average of 13.1‰ for the nine individuals from the site included in the study, as well as that for all adult LN individuals from Ust'-Ida (11.7 ± 0.8‰; Weber et al. 2011). All of the individuals sampled from the Early Bronze Age site of

Kurma XI were adult, while the single subadult from Khuzhir-Nuge XIV was aged 8–10. Following infancy, the stable isotope data indicate that children were consuming foods that were isotopically indistinguishable from those consumed by adults (Waters-Rist et al. 2011:238).

Stable carbon and nitrogen isotope measurements were made on ultrafiltered collagen samples prepared for AMS ^{14}C dating (for details see Brock et al. 2007, 2010), corrected for drift in the mass spectrometer through the use of an internal alanine standard. To ensure their replicability, two new runs from the same collagen samples were prepared with two additional standards (United States Geological Service reference material USGS40 and an internal seal collagen standard), effectively bracketing the human δ^{13}C and δ^{15}N collagen values, and allowing for a two-point calibration. The original measurements were found to be highly correlated with the duplicate runs, both with and without the two-point calibration (r^2 values > 0.995 in all instances, for both δ^{13}C and δ^{15}N). As the δ^{15}N values are the most important for the regression model (see below), Figure 3 shows the relationship between the uncalibrated single run, and the average of two calibrated runs. For the purposes of this study then, we retain the original measurements. The advantage of using these for the purposes of correcting for the reservoir effect is that this obviates the need for additional isotopic analyses in the wider Baikal project, which has a data set comprising hundreds of ^{14}C and stable isotope measurements on human bone (Weber et al. 2010, 2011), made without the two-point calibration.

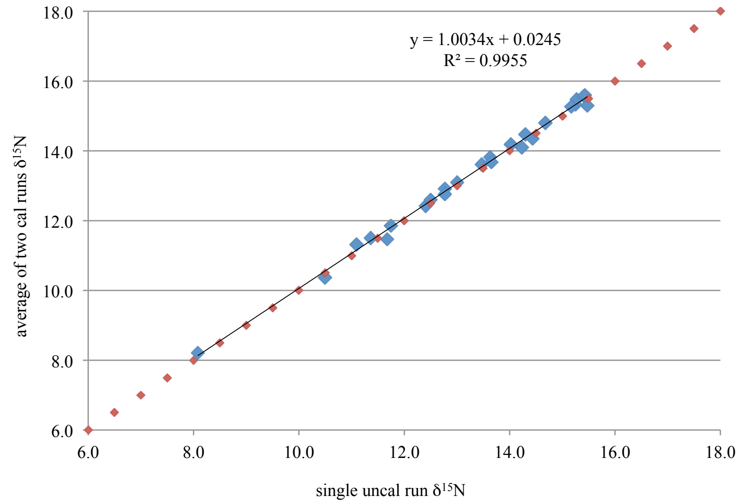

Figure 3 Bivariate plot showing near-perfect correlation (r^2 = 0.996) between uncalibrated and calibrated δ^{15}N values (see text for explanation). The small diamond symbols define a 1:1 correlation.

RESULTS

All samples were successfully analyzed, with acceptable atomic C:N ratios and collagen yields (DeNiro 1985; van Klinken 1999) (Table 2; see also online Supplementary data). In total, 83 ^{14}C determinations were made. There is a moderate positive correlation between the δ^{13}C and δ^{15}N values (r^2 = 0.291, p = 0.001; Figure 4). Eleven samples—eight human and three animal—have duplicate or triplicate AMS ^{14}C measurements, of which all but one can be successfully combined in OxCal v 4.2 (Bronk Ramsey and Lee 2013) (α = 0.05; Ward and Wilson 1978): the exception (SHA 2008.104) is considered further below. Of the 33 paired human/animal samples, eight derive from double graves with both individuals dated: two from Lokomotiv, two from Shamanka II, three from Ust'-Ida, and one from Khuzhir-Nuge XIV. In the case of the double grave from Khuzhir-Nuge

Table 2 All ^{14}C determinations and $\delta^{13}C$ and $\delta^{15}N$ values on humans (bone) and fauna (tooth) used in the analysis.

Site	OxA-	Species	^{14}C date	±	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C:N	Offset (yr)	OxA-lab nr	Species	^{14}C date	±	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C:N
Lokomotiv	26285, 26286	*H. sapiens*	6842	27	–14.8	14.9	3.2	378	26284	*Marmot* sp.	6464	36	–19.3	8.0	3.4
Lokomotiv	26288-9, 25634	*H. sapiens*	6814	22	–15.0	14.4	3.2	381	26287	*Marmot* sp.	6433	37	–20.0	6.6	3.3
Lokomotiv	26292, 26293	*H. sapiens*	6860	27	–15.2	15.0	3.2	398	26291	*Marmot* sp.	6462	36	–20.6	4.6	3.3
Lokomotiv-Raisovet	26295	*H. sapiens*	6808	37	–15.5	14.2	3.2	425	26294	*Marmot* sp.	6383	37	–20.4	6.6	3.2
Lokomotiv-Raisovet	26297	*H. sapiens*	7009	39	–14.4	15.4	3.2	512	26296	*Marmot* sp.	6497	37	–19.5	5.8	3.3
Shamanka II	26189, 26190	*H. sapiens*	6859	26	–16.4	14.1	3.2	523	26299	*Marmot* sp.	6336	35	–19.2	5.2	3.2
Shamanka II	27052	*H. sapiens*	6935	38	–15.7	15.4	3.1	622	26300	*Marmot* sp.	6313	36	–19.1	9.0	3.2
Shamanka II	21540	*H. sapiens*	6694	39	–17.7	14.2	3.2	434	26301	*Marmot* sp.	6260	36	–20.2	4.7	3.2
Shamanka II	21497, 27552, 28697	*H. sapiens*	6334	20	–16.4	13.6	3.2	–9	26302, 27553	*Marmot* sp.	6343	28	–19.9	5.9	3.2
Shamanka II	28037, 28696	*H. sapiens*	6826	25	–15.7	15.3	3.1	570	26298	*Marmot* sp.	6256	36	–19.1	6.2	3.2
Ust'-Ida	26941	*H. sapiens*	4887	29	–16.9	15.5	3.2	125	26944	*Cervus elaphus*	4762	30	–20.6	6.8	3.2
Ust'-Ida	26936	*H. sapiens*	4890	30	–17.7	12.5	3.2	184	26946	*Cervus elaphus*	4706	30	–19.4	6.9	3.2
Ust'-Ida	26939, 27153	*H. sapiens*	4874	24	–17.2	13.1	3.2	266	26948	*Cervus elaphus*	4608	30	–19.9	6.6	3.2
Ust'-Ida	26938-40	*H. sapiens*	4940	22	–17.4	13.9	3.2	329	26945	*Cervus elaphus*	4611	30	–19.2	7.7	3.2
Ust'-Ida	27055	*H. sapiens*	4876	33	–17.8	12.8	3.1	181	26943	*Cervus elaphus*	4695	32	–19.7	6.9	3.2
Ust'-Ida	26937	*H. sapiens*	4965	30	–16.0	13.6	3.2	307	26947	*Cervus elaphus*	4658	31	–19.1	7.1	3.2
Ust'-Ida	26935, 27056	*H. sapiens*	4798	23	–17.1	12.4	3.2	154	26942	*Cervus elaphus*	4644	31	–19.9	6.7	3.2
Kurma XI	25131	*H. sapiens*	3954	31	–19.1	11.7	3.2	190	26924, 26925	*Cervus elaphus*	3764	23	–19.7	4.9	3.1
Kurma XI	21956	*H. sapiens*	4207	33	–17.9	15.5	3.2	401	27025	*Cervus elaphus*	3806	31	–19.0	5.6	3.1
Kurma XI	25132, 25133	*H. sapiens*	4132	22	–18.4	15.6	3.2	423	27026	*Cervus elaphus*	3709	30	–19.8	7.0	3.1
Kurma XI	26922	*H. sapiens*	4204	31	–18.2	15.2	3.1	449	27028	*Cervus elaphus*	3755	31	–19.7	5.3	3.1
Kurma XI	26920	*H. sapiens*	4157	32	–18.6	14.7	3.1	413	27027	*Cervus elaphus*	3744	30	–18.9	7.8	3.2
Kurma XI	21955	*H. sapiens*	3979	33	–19.3	11.4	3.2	200	27030	*Cervus elaphus*	3779	30	–19.0	7.4	3.2
Kurma XI	26921	*H. sapiens*	4189	31	–18.7	14.0	3.1	416	27029	*Cervus elaphus*	3773	30	–20.0	5.7	3.1
Kurma XI	28773	*H. sapiens*	4233	31	–18.7	14.1	3.2	336	27031	*Cervus elaphus*	3897	29	–19.3	6.6	3.1
Khuzhir-Nuge XIV	26907	*H. sapiens*	3800	30	–18.9	12.4	3.2	244	26917	*Cervus elaphus*	3556	30	–19.8	7.6	3.2
Khuzhir-Nuge XIV	26908	*H. sapiens*	3803	31	–19.0	11.1	3.2	190	26918	*Cervus elaphus*	3613	31	–20.0	7.9	3.2
Khuzhir-Nuge XIV	26909, 27554	*H. sapiens*	3728	22	–19.2	11.7	3.2	118	26919	*Cervus elaphus*	3610	30	–20.0	6.1	3.1
Khuzhir-Nuge XIV	26912	*H. sapiens*	3829	29	–17.9	14.4	3.2	301	26916	*Cervus elaphus*	3528	28	–18.9	6.9	3.2
Khuzhir-Nuge XIV	26981	*H. sapiens*	3888	30	–17.6	15.8	3.2	299	26915	*Cervus elaphus*	3589	33	–19.3	6.4	3.2
Khuzhir-Nuge XIV	26910, 27619	*H. sapiens*	3790	21	–18.7	10.4	3.2	–34	27050	*Cervus elaphus*	3824	30	–19.6	6.5	3.2
Khuzhir-Nuge XIV	26911	*H. sapiens*	3833	30	–18.4	12.8	3.2	136	26913	*Cervus elaphus*	3697	31	–19.1	5.3	3.2
Khuzhir-Nuge XIV	28699	*H. sapiens*	3969	29	–16.6	16.6	3.3	379	26914	*Cervus elaphus*	3590	30	–18.9	7.5	3.2

XIV (K14 1998.037), it was possible to positively associate separate animal teeth with each individual, so that they feature separately in the analysis. In the two double graves from Shamanka II (SHA 2004.056 and SHA 2004.059), the teeth could be associated with one of the two individuals with a reasonable degree of confidence, and so only the date for that individual is used in the model.

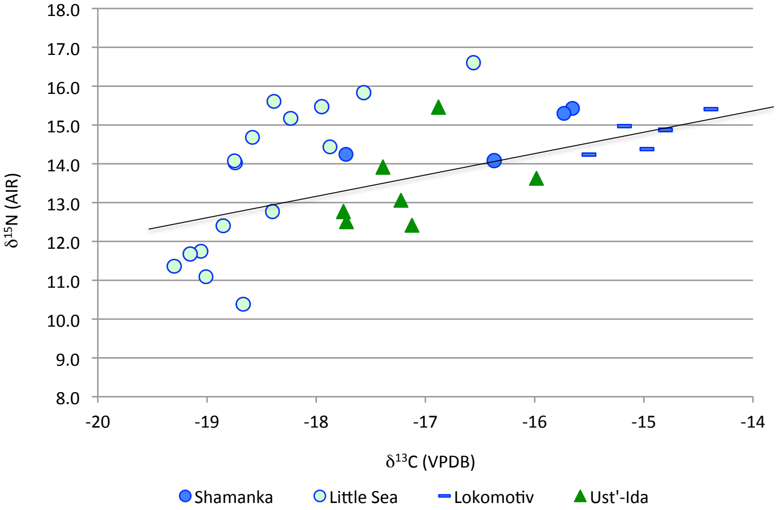

Figure 4 Bivariate plot of human bone collagen δ^{13}C and δ^{15}N values for samples included in the paired dating study (adjusted $r^2 = 0.291$, $p = 0.001$; $n = 33$).

In the remaining five cases, no such association was possible; therefore, the dated animal tooth could relate to either of the two humans from the grave. This also applies to one triple grave, with all three individuals dated (LOK 1981.024). There are three ways of addressing this issue. One approach is to combine the two/three human dates and use this as the comparandum for the animal tooth date from the same grave (Table 3). This raises the question of how to treat the associated stable isotope values for the individuals in the double/triple graves. It could be argued that the fact that the dates can be successfully combined (using R_Combine in OxCal) constitutes *prima facie* evidence that there is no significant difference in whatever offset might apply for the individuals in question, and that therefore the proportion of lake-derived protein should be similar. The absolute difference in isotopic values for the double/triple graves ranges between 0.1 and 1.5‰ for δ^{13}C, averaging 0.9 ± 0.6‰, and between 0.2 and 1.2‰ for δ^{15}N, averaging 0.7 ± 0.3‰. While slightly larger than ideal in a number of cases, the values on individuals from the same graves are reasonably consistent with one another, when seen in the context of the wider variability observed at these sites.

An alternative approach to combining the human dates from the five double graves and one triple grave is to calculate a separate offset for each of the dated individuals with their δ^{15}N values, against the single animal tooth date from the same grave. The problem with this is that it would artificially increase sample size and bias the overall results towards the offset observed in these particular graves, effectively counting each twice (and in the case of the triple grave, three times). In addition, this approach would violate the statistical assumption of independence necessary for linear regression models. A third and final approach is simply to omit the six results from double/multiple graves from the equations.

Table 3 ^{14}C determinations on humans from double/triple graves, with R_Combined dates (OxCal v 4.2) and offsets for both individual and combined human-faunal dates.

Master_ID	OxA- lab nr	^{14}C yr human	±	δ^{13}C	δ^{15}N	Offset	OxA- lab nr	^{14}C yr fauna	±
LOK_1980.022.02	26285	6808	37	–15.0	15.3	344	26284	6464	36
LOK_1980.022.03	26286	6878	38	–14.6	14.5	414			
LOK_1980.022	combined	6842	27	–14.8	14.9	378			
LOK_1981.024.01	26288	6793	36	–14.9	14.3	360	26287	6433	37
LOK_1981.024.03	26289	6868	37	–14.8	14.5	435			
LOK_1981.024.04	25634	6775	40	–15.2	14.3	342			
LOK_1981.024	combined	6830	26	–15.0	14.4	381			
LOK_1988.038.01	26292	6882	37	–14.5	15.3	420	26291	6462	36
LOK_1988.038.02	26293	6836	38	–15.9	14.7	374			
LOK_1988.038	combined	6860	27	–15.2	15.0	398			
LOK_1989.020.01	26939	4885	30	–16.8	13.5	205	26948	4680	30
LOK_1989.020.02	27153	4854	39	–17.7	12.7	174			
LOK_1989.020	combined	4874	24	–17.2	13.1	190			
UID_1989.021.01	26938	4963	32	–18.1	14.2	352	26945	4611	30
UID_1989.021.02	26940	4921	29	–16.7	13.7	310			
UID_1989.021	combined	4940	22	–17.4	13.9	329			
UID_1994.053.01	26935	4791	30	–16.6	13.0	147	26942	4644	31
UID_1994.053.02	27056	4807	35	–17.6	11.8	163			
UID_1994.053.01	combined	4798	23	–17.1	12.4	154			

In the sections that follow, we have chosen to use the averaging approach for both the offset in ^{14}C years and the stable isotope values. We have, however, also calculated separate regression equations given by the other two approaches (Table 4). The differences between the three resulting models are small, as can be illustrated by using the respective regression equations to predict the offset of a hypothetical individual with an age of 6500 ^{14}C yr, and a δ^{15}N value of 15.0‰:

- Model 1 (averaging solution), offset = –732.8 + 76.6(15.0) = 416 yr
- Model 2 (separate offsets calculated), offset = –726.4 + 76.0(15.0) = 414 yr
- Model 3 (double/triple graves omitted), offset = –737.2 + 77.1(15.0) = 419 yr

Table 4 Details of linear regression equations discussed in the text. Adjusted r^2 value is given for the Little Sea model incorporating both δ^{13}C and δ^{15}N. S is the standard deviation of the residuals.

Regression model	Equation	S	r^2	p	n
Full data set, δ^{13}C^1	1180.3 + 50.2 (δ^{13}C)	142.1	0.208	0.008	33
Full data set, δ^{15}N^1	–672.5 + 70.9 (δ^{15}N)	114.5	0.486	0.000	33
Excluding outliers, δ^{15}N^1	–732.8 + 76.6 (δ^{15}N)	85.5	0.672	0.000	31
Excluding outliers, δ^{15}N^2	–726.4 + 76.0 (δ^{15}N)	80.6	0.667	0.000	38
Excluding outliers, δ^{15}N^3	–737.2 + 77.1 (δ^{15}N)	93.2	0.668	0.000	25
SW Baikal/Angara^1	–1388.9 + 125.5 (δ^{15}N)	64.1	0.814	0.000	15
SW Baikal/Angara^2	–1165.9 + 108.6 (δ^{15}N)	69.7	0.728	0.000	22
SW Baikal/Angara^3	–1521.7 + 136.4 (δ^{15}N)	62.0	0.871	0.000	9
Little Sea, δ^{15}N	–533.9 + 59.8 (δ^{15}N)	74.9	0.723	0.000	16
Little Sea, δ^{13}C & δ^{15}N	–3329.5 – 125.6 (δ^{13}C) + 95.1 (δ^{15}N)	51.8	0.859	0.000	16

^{1}Averaging double/triple graves.
^{2}Treating double/triple graves separately.
^{3}Excluding double/triple graves.

LINEAR REGRESSION MODELS FOR THE BAIKAL FRESHWATER RESERVOIR EFFECT

The observed values for the animal-human ^{14}C offsets range from –34 to 622 ^{14}C yr. The consistently highest offsets are seen at the Early Neolithic cemeteries of Shamanka II (averaging 537 ± 80 yr) and Lokomotiv (419 ± 55 yr), with that at Shamanka II being significantly higher (Mann-Whitney U-test, $p = 0.027$). Offsets at the Late Neolithic component at Ust'-Ida average 237 ± 74 yr, while those at the Early Bronze Age sites of Khuzhir-Nuge XIV and Kurma XI on the Little Sea fall into two distinct groups irrespective of site, one averaging 149 ± 91 yr and the other averaging 380 ± 55 yr. This difference is discussed further below.

Linear regression models for the full data set ($n = 33$) indicate that δ^{13}C, while statistically significant on its own, is not of great predictive value ($r^2 = 0.208$, $p = 0.008$), and becomes insignificant in a multiple regression model with δ^{15}N. The latter on its own explains a much greater proportion of variation in the FRE ($r^2 = 0.486$, $p < 0.000$) (Table 4). However, there are a number of problematic samples in the full data set. The most obvious case for straightforward exclusion is the infant from Ust'-Ida (UID 1988.017), aged 2–4, which is clearly subject to a nursing effect, exhibiting an offset of only 125 ^{14}C yr, well below that of the 423 yr predicted for its high δ^{15}N value of 15.5‰. Indeed, we included this individual only to demonstrate the nature and extent of the problem that arises with regard to nursing infants. A regression model with the remaining 32 cases provides a much improved r^2 value of 0.588 ($p < 0.000$). The residuals from this model highlight one individual from Shamanka II (SHA 2008.104) as a clear outlier, removed by three standard deviations from the predicted offset in ^{14}C yr. This individual is also problematic in that triplicate ^{14}C determinations failed to combine (χ^2, $T = 7.15$ (6.0)), though this is a separate issue. Removing this individual further improves the predictive power of the model, increasing r^2 to 0.675 ($p < 0.000$; $n = 31$) (Figure 5), with no standardized residuals greater than 2.16. There is no pattern in the plotted residuals, suggesting that a linear regression model is appropriate (Figure 6). The regression equation is $Y = -732.6 + 76.6$ (δ^{15}N), where Y is the predicted offset between measured and actual ^{14}C age for an individual (Table 5). The slope coefficient is 76.6 ± 9.9, meaning that the predicted reservoir offset increases by ~77 yr for each 1‰ increase in δ^{15}N. Taking a complementary approach, Bronk Ramsey et al. (2014) compared an earlier form of the linear regression model presented here with a Bayesian approach that does not rely on the presence of paired dates, and so has wider utility. This yielded very similar results for the present data set (note that the regression equation in Bronk Ramsey et al. differs slightly from that presented in this paper, due to the inclusion here of additional data).

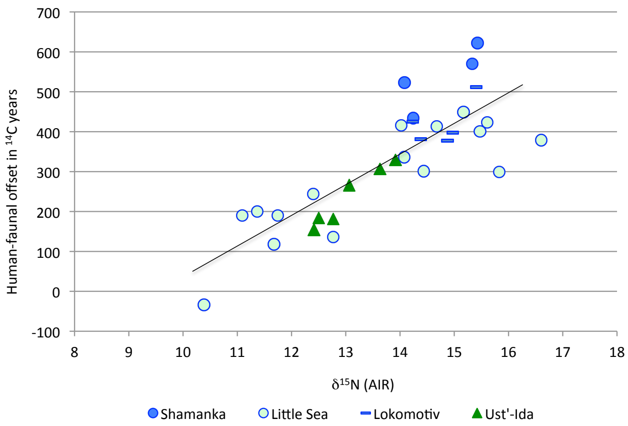

Figure 5 Linear regression plot of human δ^{15}N values and human-faunal ^{14}C offsets and ($r^2 = 0.672$, $p < 0.000$; $n = 31$; excluding Ust'-Ida infant and Shamanka II outlier).

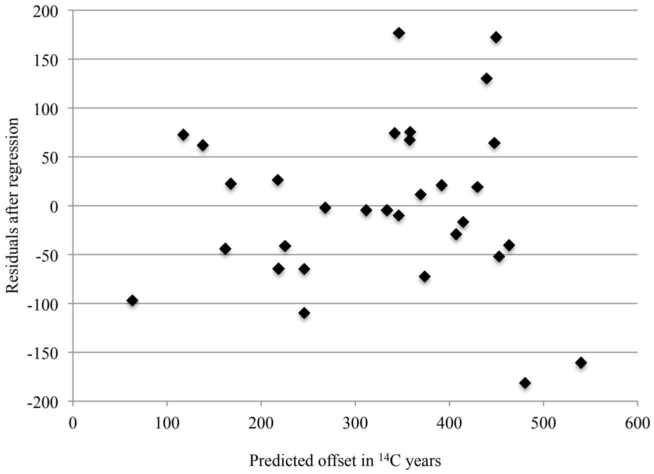

Figure 6 Bivariate plot of predicted offsets in ^{14}C yr against residuals after regression, showing absence of patterning.

Table 5 Predicted offset (*Y*) in ^{14}C yr between human and animal tooth dates from the same grave. "Residual" refers to the difference between the predicted (on the basis of δ^{15}N values) and observed offset in each case.

Sample	Predicted *Y*	Residual	Standard residuals
SHA_2004.039	346	177	2.10
SHA_2004.056.02	449	173	2.05
SHA_2005.059.02	359	75	0.90
SHA_2001.016	440	130	1.55
LOK_1980.022.02-03	407	–29	–0.35
LOK_1981.024.01-03	369	12	0.14
LOK_1988.038.01-02	415	–17	–0.20
LOR_1980.003.01	358	67	0.80
LOR_1997.011	448	64	0.76
UID_1988.018	225	–41	–0.49
UID_1989.020.01-02	268	–2	–0.02
UID_1989.021.01	334	–5	–0.05
UID_1991.041	246	–65	–0.77
UID_1994.052	312	–5	–0.06
UID_1994.053.01-02	219	–65	–0.77
KUR_2002.001	168	22	0.27
KUR_2002.003	453	–52	–0.62
KUR_2002.004	463	–40	–0.48
KUR_2002.005	430	19	0.23
KUR_2002.006	392	21	0.25
KUR_2002.012	138	62	0.73
KUR_2002.013	342	74	0.88
KUR_2003.018	346	–10	–0.12
K14_1998.036.01	218	26	0.31
K14_1998.037.01	117	73	0.86
K14_1998.037.02	162	–44	–0.52
K14_1999.045	374	–73	–0.86
K14_1999.049	480	–181	–2.16
K14_2000.077	63	–97	–1.15
K14_2001.087	246	–110	–1.30
K14_1999.057.02	540	–161	–1.91

While the regression equation given for the overall data set performs reasonably well, Figure 5 suggests the presence of two different relationships between $\delta^{15}N$ and animal-human offsets in ^{14}C yr, one related to southwest Lake Baikal and the Angara and the other to the Little Sea sites (Figure 1). A linear regression model (using the averaging approach for the double/triple graves) for the southwest Baikal/Angara sites of Shamanka II, Lokomotiv, and Ust'-Ida using $\delta^{15}N$ alone provides an r^2 value of 0.814 ($p < 0.000$), a significant improvement over that of 0.675 in the overall data set (Table 4, Figure 7). As in the overall model, $\delta^{13}C$ makes no significant added contribution to predicting the offset.

Shamanka II is located on the southwest shore of Lake Baikal. As noted above, excluding one outlier, it has the highest ^{14}C offsets observed in the present study. Lokomotiv is located within the modern city of Irkutsk. Between Irkutsk and Baikal, all water in the Angara is essentially of Lake Baikal origin and this section of the river is an important transition with regard to the nature of its fisheries. According to Kozhov's (1950) study, which predates the ecological changes in the Angara affected by the construction of three dams, this is the only section of the river with large populations of fishes (black grayling [*Thymallus arcticus baicalensis* Dybowski] and lenok [*Brachymystax lenok* Pallas]) migrating there from Baikal while no fishes present in the other, downstream, sections of the Angara enter the lake. Incidentally, modern black grayling and lenok from Bol'shie Koty, on the lakeshore only ~30 km east from the source of the Angara, show evidence of elevated $\delta^{13}C$ values (Weber et al. 2002, 2011). Thus, the communities using Lokomotiv for burial must have been consuming considerable amounts of fish from Baikal containing old carbon from the lake, and so be subject to a large freshwater reservoir effect, as observed.

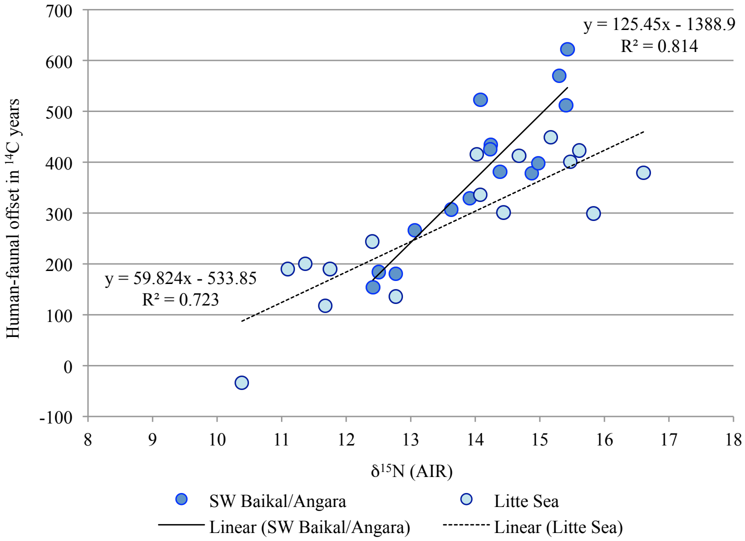

Figure 7 Linear regression plots of human $\delta^{15}N$ values and human-faunal ^{14}C offsets for the SW Baikal/Angara ($r^2 = 0.814$, $p < 0.000$; $n = 15$) and Little Sea subregions ($r^2 = 0.723$, $p < 0.000$; $n = 16$). A multiple regression model (not shown) for the Little Sea including both $\delta^{13}C$ and $\delta^{15}N$ has higher predictive power ($r^2 = 0.859$, $p < 0.000$; $n = 16$).

Ust'-Ida is also located on the Angara River, but further downriver from Lokomotiv and over 200 km from Lake Baikal (Figure 1). The waters contributed by three large rivers (Irkut, Kitoi, and Belaia) and a number of smaller streams entering downriver from Irkutsk significantly dilute the contribution of Baikal water to the Angara, so that this section of the river is expected to have a reduced offset. Also, the numerous fish species available in this section of the river do not migrate here from Baikal and thus do not carry with them that lake's ^{14}C offset. In fact, the observed average reservoir effect of 237 ± 74 yr at Ust'-Ida is approximately half that of the 471 ± 88 yr seen at Lokomotiv and Shamanka II. δ^{15}N alone is a particularly strong predictor for individuals from Ust'-Ida ($r^2 = 0.926$, $p = 0.001$), though this may be due to its small sample size of only six paired results. No similar site-based models are currently possible for Shamanka II or Lokomotiv, though further paired ^{14}C dating is planned for Shamanka II, and we expect to produce a new model specific to this important Early Neolithic cemetery in due course.

A linear regression model for the 16 paired dates from the Early Bronze Age sites of Kurma XI and Khuzhir-Nuge XIV on the Little Sea, presents a strong positive correlation between δ^{15}N and ^{14}C offset ($r^2 = 0.723$, $p < 0.000$), though it is not a significant improvement on that of the data set as a whole (Figure 7). However, and in contrast to both the overall data set and to southwest Baikal/Angara, a multiple regression model indicates that both δ^{13}C and δ^{15}N make significant contributions to predicting human-animal ^{14}C offsets in the Little Sea region (adjusted $r^2 = 0.878$; δ^{13}C $p < 0.001$; δ^{15}N $p < 0.000$) (Table 4). This does present a marked improvement over the model for the data set as a whole. It should be noted that, as is apparent from Figure 4, there is clear multicollinearity between the two predictor variables (δ^{13}C and δ^{15}N), so that the fact that the regression coefficient for δ^{13}C is negative cannot be interpreted as a negative correlation, as it would in a model with a single independent variable (Kutner et al. 1996).

The Little Sea individuals clearly fall into two groups, one with high δ^{15}N values and similar offsets to Shamanka II/Lokomotiv, and another with much lower offsets. This relationship is worth exploring in more detail. The individuals from these sites previously have been suggested to fall into two dietary groups based on their stable isotope results: those with a game-fish (GF) diet and those with a game-fish-seal (GFS) diet (Weber and Bettinger 2010; Weber et al. 2011, 2012). Dividing the results on this basis shows a clear distinction in the size of the human-faunal ^{14}C offset, averaging 149 ± 91 yr for the GF group compared to 380 ± 55 yr for the GFS group (Table 6). Of course, there is also a significant difference in the average δ^{15}N values for the two groups, as this was how they were defined in the first place. The average δ^{13}C values for the GFS group are also slightly but significantly higher (heteroscedastic Student's *t* test: $t = 3.265$, $p = 0.007$, $df = 12$). Isotopic measurements on both modern and prehistoric seals from Lake Baikal have shown that they exhibit depleted rather than elevated δ^{13}C values (Yoshii et al. 1999; Weber et al. 2011: Tables 4 and 5; Katzenberg et al. 2012: Table 5). It is predominantly the inshore fish reliant on the benthic zone that show high δ^{13}C values, whereas the Baikal seal's main prey are pelagic bullheads and sculpins (Pastukhov 1993). This suggests that those in the GFS group made greater use of Baikal's shallow-water fish as well as of seals, both of which would presumably contribute to the ^{14}C offset, though whether or not this contribution would be equal is unclear (i.e. is the carbon reservoir age the same for shallow and deep waters in Lake Baikal, as has been assumed?). The shallow-water fishery was a productive one, and fish may have been taken with nets as well as hook and line (Losey et al. 2012). Nevertheless, seals must have featured strongly in the diets of many individuals (i.e. those in the GFS group) in the Little Sea microregion, given that δ^{15}N values as high as those seen elsewhere, yet δ^{13}C values are significantly lower than in Shamanka II and all the sites along the Angara, including Ust'-Ida, furthest from the lake (Figure 4). The pelagic fish species do not seem to have been accessible to humans, given their near-complete absence from the region's ichthyofaunal assemblages (Losey et al. 2008).

The impact of the different offsets for the two Little Sea dietary groups on their archaeological interpretation can be seen in Table 6. Without the paired human-faunal dates and the offset that this provides, the observed isotopic/dietary differences might be interpreted diachronically, since the individuals in the GFS group are on average some 250 ^{14}C yr older than those in the GF group. It is clear from the terrestrial fauna dates from the same graves, however, that the individuals are contemporaries. Interestingly, all those in the GF group are thought to have been incomers to the Little Sea, originally from the Upper Lena region (Weber et al. 2011; Weber and Goriunova 2013). Isotopically, humans from the Lena region are similar to those of the GF group of the Little Sea (Weber et al. 2002, 2011). The fact that the individuals from Kurma XI and Khuzhir-Nuge XIV with this diet still exhibit a ^{14}C offset (149 ± 91 yr) indicates that either (1) they spent some years prior to their death consuming fish from the Little Sea; (2) they were highly mobile throughout the course of their lives, traveling regularly between the Lena and the Little Sea and consuming the foods of both regions; or (3) the waters of the Upper Lena River system (with no connection to Lake Baikal) have their own, albeit lower, ^{14}C reservoir age (Weber and Goriunova 2013 and see below).

Table 6 Human δ^{13}C and δ^{15}N values and ^{14}C offsets (paired human-faunal dates) for the Little Sea sites of Kurma XI (KUR) and Khuzhir-Nuge XIV (K14).

Sample ID	δ^{13}C (‰)	δ^{15}N (‰)	OxA- human bone	^{14}C yr	±	OxA- deer teeth	^{14}C yr	±	^{14}C offset
Game/Fish diet									
KUR_2002.001	–19.1	11.7	25131	3954	31	26924/5	3764	23	190
KUR_2002.012	–19.3	11.4	21955	3979	33	27030	3779	30	200
K14_1998.036.01	–18.9	12.4	26907	3800	30	26917	3556	30	244
K14_1998.037.01	–19.0	11.1	26908	3803	31	26918	3613	31	190
K14_1998.037.02	–19.2	11.7	26909/27554	3729	22	26919	3610	30	118
K14_2000.077	–18.7	10.4	26910/27619	3790	21	27050	3824	30	–34
K14_2001.087	–18.4	12.8	26911	3833	30	26913	3697	31	136
Average =	*–18.9*	*11.6*		*3841*			*3692*		*149*
1σ =	*0.3*	*0.8*		*91*			*101*		*91*
Game/Fish/Seal diet									
KUR_2002.003	–17.9	15.5	21956	4207	33	27025	3806	31	401
KUR_2002.004	–18.4	15.6	25132/3	4132	22	27026	3709	30	423
KUR_2002.005	–18.2	15.2	26922	4204	31	27028	3755	31	449
KUR_2002.006	–18.6	14.7	26920	4157	32	27027	3744	30	413
KUR_2002.013	–18.7	14.0	26921	4189	31	27029	3773	30	416
KUR_2003.018	–18.7	14.1	28773	4233	31	27031	3897	29	336
K14_1999.045	–17.9	14.4	26912	3829	29	26916	3528	28	301
K14_1999.049	–17.6	15.8	26981	3888	30	26915	3589	33	299
K14_1999.057.02	–16.6	16.6	28699	3969	29	26914	3590	30	379
Average =	*–18.1*	*15.1*		*4090*			*3710*		*380*
1σ =	*0.7*	*0.9*		*153*			*119*		*55*

The overall conclusion is that, based on present evidence, both δ^{13}C and δ^{15}N should be considered when correcting ^{14}C determinations on human bone in the Little Sea region, while δ^{15}N alone is a good estimator of the necessary FRE correction for the southwest Baikal/Angara region. This is justified both by the significantly improved predictive power of the separate models, and by the distinct ecologies of the microregions. For sites on or near the lake, but outside of these two areas, or of unknown provenance, the δ^{15}N model for the overall data set would be the most appropriate. The situation along the Angara River is particularly interesting, since reservoir effects originating in the lake would be expected to be increasingly diluted further downriver, due to increasing inputs from tributaries and the abovementioned longitudinal changes in its fishery (assuming that the tributaries themselves do not exhibit a reservoir effect).

At the same time, δ^{15}N values would remain relatively high (compared to terrestrial groups), as hunter-gatherer populations living near the river would be expected to make use of its fish resources. This seems to be borne out by our results, with individuals from Ust'-Ida exhibiting significantly lower δ^{15}N values and ^{14}C offsets—and lower δ^{13}C and δ^{15}N values both in the present study and in the larger isotopic data set (Weber et al. 2002, 2011)—than seen at Lokomotiv. There is a significantly stronger correlation between δ^{15}N values and ^{14}C offsets at Ust'-Ida than in the regional model for southwest Baikal/Angara, perhaps justifying the use of a separate regression equation for this site, though the smaller sample size on which it is based needs to be taken into account. This trend might be expected to continue further downriver, presumably eventually reaching a point where no ^{14}C offset of Baikal origin was discernable. It is possible, however, that the dilution with increasing distance from the lake could be replaced with offsets of some other source. Unfortunately, studies of the isotope ecology of the modern river system do not provide a good proxy because of the large hydroelectric dams constructed on the Angara in the 1950s (Irkutsk), 1960s (Bratsk), and 1970s (Ilimsk). Further research is being undertaken on offsets between archaeological human and animal bone seen in the wider region, to determine the extent of any riverine offsets in other systems. The Upper Lena, for example, flows over Precambrian and Cambrian limestone that might be expected to contribute old carbon to its watershed.

MAXIMUM AND MINIMUM RESERVOIR EFFECTS

The residence time for water in Lake Baikal has been estimated as about 377 yr (Afanas'ev 1960). However, the offsets observed in the present program of paired human-animal ^{14}C determinations suggest that this is too low, or, more probably, that additional factors are at work besides water residence time. The highest observed offset in the present data set is 622 yr (SHA 2004.056-02), and for this to be the maximum possible offset would require that all of this individual's protein over the last 10 or more years of their life was obtained from the lake. This is highly unlikely, not only theoretically, but on the basis of the abundant archaeological and isotopic evidence for the importance of hunted game to all culture groups across all periods represented in the study area (Weber et al. 2011).

Another way to approach the question of the lake's maximum reservoir age emerges from a recent comparison of AMS ^{14}C dates on seal and terrestrial bone from the same levels at the stratified site of Sagan-Zaba II (Nomokonova et al. 2013). This study suggests a minimum offset of 700 yr [interestingly, this is the same figure proposed by Seal and Shanks (1998) in an independent study of δ^{18}O and δD systematics in Lake Baikal]. As seals would be acquiring all of their protein from the lake (there is no evidence for their entering rivers), this can be taken as a conservative estimate of the reservoir age. It is then possible to use the well-studied δ^{15}N values of Baikal seals to estimate the corresponding δ^{15}N value of a hypothetical human consumer subsisting exclusively on seals. This value in turn can be entered into the linear regression equation presented above to see whether the predicted offset is similar to the proposed offset of 700 yr. Being top predators in the Baikal ecosystem (aside from humans), seals provide the most robust means of determining the expected δ^{15}N value for humans acquiring all of their protein from the lake's pelagic waters, the likely source of the highest ^{14}C offset in human bones. Of course, individuals with lower δ^{15}N values may still obtain all their protein from the lake, but from lower trophic-level sources such as the inshore fishes. Currently, there is no archaeological evidence of harvesting the omul (*Coregonus autumnalis migratorius*), the other abundant pelagic food source, by the hunter-gatherer groups in question (although omul's δ^{15}N values are much lower, 9–12‰, than those of the seal; Weber et al. 2011). The only other species with equally elevated, and indeed occasionally higher, δ^{15}N values is pike (*Esox lucius*) (Weber et al. 2002; Katzenberg et al. 2012); however, measurements for this nonmigratory species are much more heterogeneous, reflecting their more varied feeding habits. Additionally, pike will be present in both the lake and its rivers, not all of which will be subject to the same ^{14}C reservoir offset.

Stable nitrogen isotope measurements on 46 archaeological Baikal seals average 14.3 ± 1.2‰ [Katzenberg et al. 2012; Baikal-Hokkaido Archaeological Project (BHAP)/Research Laboratory for Archaeology and the History of Art (RLAHA) data]. Measurements for 45 modern seals are slightly lower, averaging 13.9 ± 0.3‰ (Yoshii et al. 1999; Weber et al. 2002; Katzenberg et al. 2012); this difference, while small, is statistically significant ($t = 2.23$, $p = 0.030$), and the archaeological value of 14.3‰ is therefore preferred for the calculation. While stepwise ^{15}N trophic level enrichment is well-documented in general (Schoeninger et al. 1983; Minagawa and Wada 1984), the precise value appropriate to humans is still debated (Bocherens and Drucker 2003; Hedges and Reynard 2007). Many recent studies advocate using a range of 3–5‰ rather than a single value to better reflect this uncertainty.

Modeled ^{14}C offset: $-732.8 + 76.6\,(\delta^{15}\text{N})$

$$-732.8 + 76.6\,(14.3{+}3‰) = 593 \text{ yr}$$

$$-732.8 + 76.6\,(14.3{+}4‰) = 670 \text{ yr}$$

$$-732.8 + 76.6\,(14.3{+}5‰) = 746 \text{ yr}$$

Employing this range of δ^{15}N enrichment values in the regression equation presented above provides estimated ^{14}C reservoir offsets of 593, 670, and 746 yr, respectively. The middle offset, employing a prey-consumer enrichment of 4‰, is closest to the anticipated offset of 700 yr (Figure 8). Despite the relatively minor differences relating to varying trophic enrichment values, the regression equation itself performs well, and imparts a degree of confidence in the models presented here. It is important to stress that the offset calculated for seals at Sagan-Zaba II (Nomokonova et al. 2013) is entirely independent of the offset model based on human-animal paired dating.

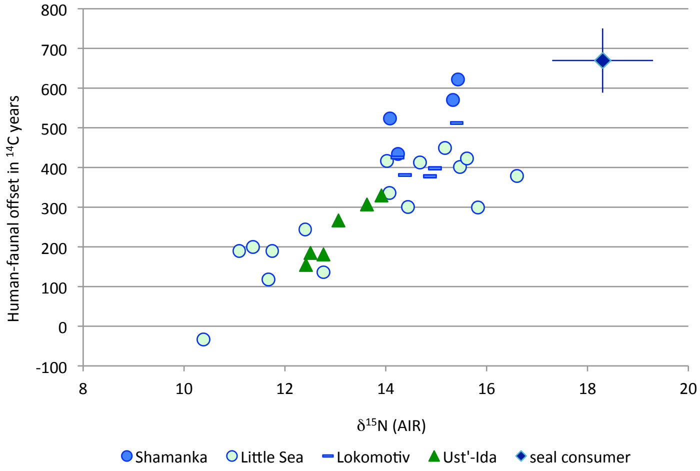

Figure 8 Bivariate plot of human-faunal ^{14}C offset and human δ^{15}N values, with addition of a hypothetical human consuming only seals (based on a seal δ^{15}N value of 13.4‰ and prey-consumer trophic level shift of 4‰).

Conversely, solving the regression equation in reverse, i.e. for no offset (0 yr), gives a predicted δ^{15}N value of 9.56‰. Of course, as with any regression model, the incorporation of additional data points will modify the equation, and further research is required to refine both extremes of the relationship. In fact, human δ^{15}N values of less than 10‰ are very rare in the Cis-Baikal data set (Weber et al. 2011; Katzenberg et al. 2012), and likely do reflect diets with minimal contribution from freshwater fish (as most of the burial sites are near the lake or rivers, there may be few communities/individuals in the region who did not make substantial use of freshwater fish). The lowest value in the current study is 10.4‰ for an individual from Khuzhir-Nuge XIV (K14_2000.077), and this is associated with a ^{14}C offset of –34 yr. That the offset is negative is presumably simply a result of random noise, i.e. the associated uncertainties in the ^{14}C and $\delta^{15}N$ measurements on both human and animal samples. Essentially, the offset of –34 yr can be considered as no difference between the human and animal ^{14}C ages, which indeed can be successfully combined (χ^2, $T = 0.9$ (3.8)).

CONCLUSIONS

Paired dating of prehistoric human bone and terrestrial fauna teeth from the same graves has provided a means of investigating the freshwater reservoir effect at Lake Baikal. Due to the complex ^{13}C ecology of the lake, $\delta^{15}N$ proved more useful in predicting the extent of the observed ^{14}C offsets. Excluding two outliers, a linear regression model using $\delta^{15}N$ alone accounted for some 67% of the observed variability in ^{14}C offsets. This was substantially improved upon through the use of two separate models, one for SW Baikal/Angara and another for the Little Sea, respectively accounting for about 81% and 86% of the variability in ^{14}C offsets. While $\delta^{13}C$ was of little or no predictive value either in the data set as a whole or in the SW Baikal/Angara subset, a higher r^2 value was obtained in the Little Sea region using both $\delta^{13}C$ and $\delta^{15}N$. For these two areas then, the use of separate regression models is warranted. For sites outside of these areas, or for individuals of uncertain provenance, the general $\delta^{15}N$ model is to be preferred.

This study presents an unusually successful application of the use of stable isotope data to predict the FRE in humans. Other studies have found either no correlation (Wood et al. 2013) or identified a freshwater diet offset, but lacked sufficient data to investigate it in detail (Cook et al. 2001; Lillie et al. 2009). That is not to say that there are no remaining issues in Cis-Baikal to be addressed. Correcting the dates for nursing infants using $\delta^{15}N$ values will be problematic. As a first approximation, one could subtract the assumed trophic level effect of ~3‰, but whether or not the entire value should be applied would depend on the age of the infant as well as the onset and nature of weaning practices for both that society and for the individual in question. Other important questions regard the extent to which there are differences in the ^{14}C age of waters in the three deep basins of Lake Baikal as well as in its shallow coves, lagoons, and gulfs—the former the source of the seal, the latter the source of the harvested inshore fishes. The frequently reported residence time of 377 yr for water in Lake Baikal is based, as mentioned earlier, on a relatively simple calculation of the water inflow and outflow and the lake's total water volume as well as an implicit assumption of even mixing rates of water throughout the entire lake including the three deep basins, the bays and gulfs (Chivyrkui, Proval, Barguzin, and Little Sea), and the shallow coves and lagoons (Kurkut, Mukhor, Kurma, Posol'sk). In fact, it is more realistic to expect rather uneven and perhaps quite variable mixing rates, but a systematic study of this matter has not yet been undertaken. Another question concerns the assessment of the distribution of the FRE along the Angara, as well as the possibility of separate sources of old carbon in other watersheds, such as the Upper Lena.

A detailed consideration of the regression model's impact on the current cultural historical framework is underway and will appear in a future publication. While much work remains to be done, our initial results are very promising, and offer an improved chronological framework for the region and important insights for hunter-gatherer research in other culturally and ecologically similar settings.

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