

HIGHLY VARIABLE FRESHWATER RESERVOIR OFFSETS FOUND ALONG THE UPPER LENA WATERSHED, CIS-BAIKAL, SOUTHEAST SIBERIA

Rick J Schulting^{1,2} • Christopher Bronk Ramsey¹ • Vladimir I Bazaliiskii³ • Andrzej Weber⁴

ABSTRACT. A program of paired dating of human and faunal remains on a sample of 11 prehistoric (Mesolithic/Neolithic to Early Bronze Age) graves in the Upper Lena basin, southeast Siberia, was initiated to investigate the freshwater reservoir effect (FRE). The results show the presence of a substantial but highly variable offset, ranging from 255 to 1010 ¹⁴C yr. In contrast to previous studies centered on Lake Baikal and the Angara River, human stable nitrogen isotope values show little or no correlation with the radiocarbon offset, despite the clear trophic differences seen in $\delta^{15}\text{N}$ between terrestrial and aquatic sources of protein in the region's isotope ecology. However, stable carbon isotope measurements show a moderate negative correlation of some predictive value ($r = -0.70$, $p = 0.016$, $df = 10$). Two different regression equations have been calculated, the first using human $\delta^{13}\text{C}$ values for the entire data set ($r^2 = 0.49$) and the second, using both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, limited to the Early Bronze Age of the southern Upper Lena ($r^2 = 0.84$, $p = 0.030$, $df = 5$). The source of the old carbon in the Upper Lena River system is not clear. While the river flows over carbonate bedrock and is moderately alkaline, we suggest that old terrestrial carbon entering the riverine foodweb through bank erosion and other processes is a more likely candidate for the majority of the ¹⁴C offset.

INTRODUCTION

Previous research on the freshwater reservoir effect (FRE) in the waters of Lake Baikal and its main outflow, the Angara River, has demonstrated a substantial “old carbon” offset, of up to 700 ¹⁴C yr (Nomokonova et al. 2013; see also Prokopenko et al. 1999). Since prehistoric hunter-gatherers living around the lake generally made extensive use of its fishes and seals (Katzenberg and Weber 1999; Katzenberg et al. 2009, 2010, 2012; Weber and Bettinger 2010; Weber et al. 2011), this offset is apparent to varying degrees when human bone collagen is radiocarbon dated. Investigation of the offset was undertaken through paired dating of human bone and associated animal teeth from the same graves, with strong correlations being found between the extent of the offset in ¹⁴C yr and human stable isotope values (Bronk Ramsey et al. 2014; Schulting et al. 2014). Stable nitrogen isotopes ($\delta^{15}\text{N}$) proved to be a good predictor, accounting for nearly 70% of the variation in the human-animal ¹⁴C offset for the Cis-Baikal region overall. Dividing the results by region further improved the regression models, with $\delta^{15}\text{N}$ alone accounting for over 80% of the variation in the Angara/SW Baikal microregion, and, when combined with stable carbon isotope ($\delta^{13}\text{C}$) values, 85% for the Little Sea microregion (Schulting et al. 2014: Table 4). Here, we expand on this research by presenting new data from the Upper Lena watershed located to the north of Lake Baikal (Figure 1), but unconnected to it, and hence potentially subject to a different FRE.

Understanding the FRE for the Upper Lena system is important in terms of being able to provide a single coherent chronological framework within which to investigate multiple aspects of mid-Holocene hunter-gatherer culture history and social and environmental dynamics in the Cis-Baikal region. In particular, a relationship has been posited between the sites of the Little Sea microregion of Lake Baikal (defined by the area between the mainland and Ol'khon Island) and those of the Upper Lena, in which individuals from the latter were buried in the Early Bronze Age cemeteries of the Little Sea, most notably Khuzhir-Nuge XIV (Weber and Goriunova 2013). More widely, the rich archaeological record of the Baikal region, especially its wealth of mortuary data, can serve to provide insights into the complex interrelationships between northern Eurasian hunter-gatherer subsistence economies, mobility, and social structure (Weber and Bettinger 2010).

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.

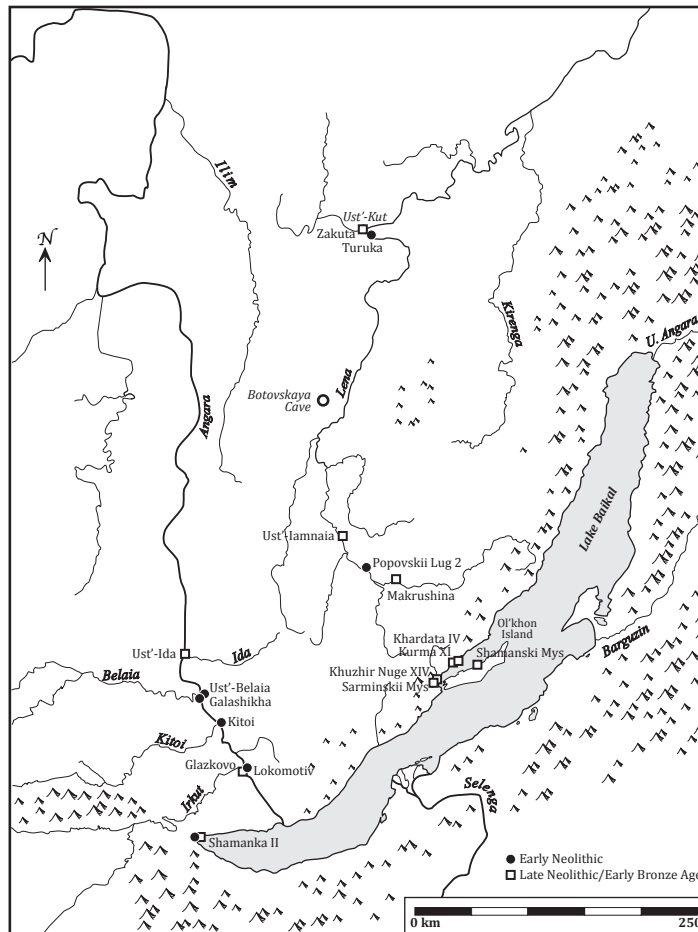


Figure 1 Map of the Baikal region, showing the locations of selected cemetery sites.

MATERIALS AND METHODS

Eleven paired human-animal dates from the same graves were obtained from five sites in the Upper Lena River system: one from Popovskii Lug 2, two each from Turuka and Zakuta, and three each from Ust'-Iamnaia and Makrushino (Figure 1). On typological criteria, these graves can be attributed to the Late Mesolithic/Early Neolithic transition (Popovskii Lug 2), Early Neolithic (Turuka), Late Neolithic (Zakuta), and Early Bronze Age (Ust'-Iamnaia and Makrushino). As is the case across Cis-Baikal, these culture-historical designations refer to various elements of the mortuary rites and to the presence of diagnostic material culture (pottery in the case of the Neolithic, and imported bronze in the case of the Early Bronze Age). In terms of their subsistence economy, all are hunter-gatherers. Nine human samples are from adults; we lack data on sex determination, with the exception of two probable females. Because of the limited number of adult graves with terrestrial material in firm association, three subadult samples (two infants of <3 yr and one child <7 yr age) are also included, though these do present potential complications in terms of their $\delta^{15}\text{N}$ values due to the nursing effect (Waters-Rist et al. 2011; see also Schulting et al. 2014). This issue is addressed below. The animal samples from the same graves comprised both bone and tooth artifacts, which could be clearly associated with their respective interments.

In addition to the prehistoric human and faunal remains, we include ^{14}C dating of bone from a modern pike (*Esox lucius*), collected in 2002 from the Lena River near Ust'-Kut (in the vicinity of

Turuka and Zakuta) as part of an extensive study of the region's stable isotope ecology (Katzenberg et al. 2010, 2012; Weber et al. 2011).

Sample preparation and accelerator mass spectrometry (AMS) ^{14}C and stable carbon and nitrogen isotope measurement followed the protocols in place at the Research Laboratory for Archaeology and the History of Art (RLAHA) (Brock et al. 2010). As is now standard at RLAHA, a 30kD ultrafiltration step was employed (Brock et al. 2007, 2010). Stable isotope measurements were made on the same ultrafiltered collagen extraction. Precision is on the order of ± 0.2 for $\delta^{13}\text{C}$ and ± 0.3 for $\delta^{15}\text{N}$.

For the analysis of the results, parametric statistical tests (Student's t tests) are used where there is no evidence for significant departure from a normal distribution (as assessed by Shapiro-Wilk's W). Nonparametric tests (Mann-Whitney U tests) are used when the data depart from normality.

RESULTS

Results are presented in Table 1. All samples yielded good-quality collagen based on collagen yield and atomic C/N ratios (DeNiro 1985; van Klinken 1999). The observed offsets between the 11 paired human and animal ^{14}C estimates range from 255 to 1010 ^{14}C yr, averaging 592 ± 244 ^{14}C yr. Two samples were dated in duplicate, with the resulting determinations successfully combined in OxCal v 4.2 (Bronk Ramsey and Lee 2013) using the R_Combine function.

Human $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values average $-19.8 \pm 0.4\text{‰}$ and $12.8 \pm 0.8\text{‰}$, respectively. There is no evidence for any correlation between the two isotopes ($r^2 = 0.006$, $p = 0.826$; Spearman's $r = -0.264$, $p = 0.433$). Faunal stable isotope values (primarily *Cervus elaphus*/Cervidae, with one *Sus scrofa*) average $-20.2 \pm 1.1\text{‰}$ and $5.3 \pm 0.9\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively. These data are useful in supporting the likelihood that freshwater fish are contributing significantly to human diets along the Lena, since the average human $\delta^{15}\text{N}$ value of $12.8 \pm 0.8\text{‰}$ is clearly more than one trophic level above that of the herbivores at $5.3 \pm 0.9\text{‰}$ (Minagawa and Wada 1984; Bocherens and Drucker 2003; Hedges and Reynard 2007).

The modern pike from Ust'-Kut provided a ^{14}C determination of 1373 ± 26 BP (OxA-V-2585-23). This is an underestimation of the actual old carbon offset, since additional ^{14}C from atmospheric nuclear bomb testing from the 1950s to early 1960s needs to be taken into account (Stenhouse and Baxter 1979; Uno et al. 2013). Stable isotopes for this specimen measured -24.6‰ for $\delta^{13}\text{C}$ and 10.8‰ for $\delta^{15}\text{N}$. To enable comparison with pre-modern measurements, the $\delta^{13}\text{C}$ value needs to be adjusted by about $+1.5\text{‰}$ for atmospheric depletion caused by fossil fuel burning (Keeling 1979; Gruber et al. 1999), giving a value of -23.1‰ . Comparable $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values have been found in other modern fish from the Upper Lena (Table 2).

There is a moderate but significant negative correlation between human $\delta^{13}\text{C}$ values and human-animal offsets in ^{14}C years ($r = -0.70$, $r^2 = 0.490$, $p = 0.016$, $df = 10$) (Figure 2). The corresponding regression equation is $Y = -7364.2 - 402.4 (\delta^{13}\text{C})$, where Y is the predicted offset between measured and actual age of an individual in ^{14}C yr. That is, for every 1‰ decrease in $\delta^{13}\text{C}$, the offset increases by 404 ^{14}C yr. What is particularly striking about this correlation is that it occurs over a range of only 1.5‰. Unfortunately, it is not possible to extend this range, given the restricted variation in human $\delta^{13}\text{C}$ values found in the Upper Lena, and the fact that the few individuals with slightly higher values (none are lower: Weber et al. 2002; ORAU unpublished data) do not have associated terrestrial materials for paired dating. There is no relationship between the ^{14}C offset and $\delta^{15}\text{N}$ ($r^2 = 0.001$, $p = 0.946$, $df = 10$) in the overall data set, irrespective of the inclusion or exclusion of the three subadult samples ($r^2 = 0.014$, $p = 0.778$, $df = 7$), which in any case do not show significant elevation above the adults (Table 1 and Figure 3).

Table 1 ^{14}C , $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ results on humans and fauna from the Upper Lena.

Site	Master_ID	Period	Age	OxA-	^{14}C yr	%Yld	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	C:N	Offset	Species	Material	OxA-	^{14}C yr	%Yld	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	C:N
Popovskii Lug 2	POP2_2010.001	LM/ EN	adult	27119	8070 ± 45	14.9	-19.8	12.4	3.2	913	Cervidae	bone	28700	7157 ± 36	6.4	-18.5	3.5	3.3
Turuka	TUR_1993.005	EN	adult	25489	7136 ± 35	5.8	-20.1	13.2	3.3	834	<i>Cervus elaphus</i>	tooth	28776	6302 ± 34	1.8	-19.7	5.7	3.4
Turuka	TUR_1992.004	EN	adult	25573	6980 ± 40	1.9	-20.6	13.0	3.3	1010	<i>Cervus elaphus</i>	bone	28775	5970 ± 33	1.5	-21.5	4.0	3.5
Zakuta	ZAK_1994.002	LN	adult	25499	5189 ± 30	16.2	-19.6	12.1	3.2	746	<i>Sus scrofa</i>	tooth	28701	4443 ± 30	9.9	-19.0	4.4	3.3
Zakuta	ZAK_1994.005	LN	adult	25576	4926 ± 33	16.7	-20.0	12.4	3.2	416	Cervidae	tooth	28702/3	4510 ± 21	9.9	-22.1	5.6	3.3
Makrush- ino	MAK_1992.018	EBA	adult	28758	4490 ± 31	15.4	-19.5	14.7	3.3	493	<i>Cervus elaphus</i>	tooth	28764	3997 ± 29	14.1	-20.9	6.1	3.3
Makrush- ino	MAK_1992.013	EBA	adult	28757	4242 ± 30	14.9	-19.2	13.0	3.3	388	<i>Cervus elaphus</i>	tooth	28763	3854 ± 29	14.3	-19.6	5.6	3.3
Makrush- ino	MAK_1992.019	EBA	subadult	28759	4199 ± 30	9.7	-19.1	12.1	3.3	255	<i>Cervus elaphus</i>	tooth	28765	3944 ± 28	13.3	-20.9	6.2	3.3
Ust' Iamnaia	UIA_1977.001	EBA	subadult	28766	4142 ± 29	12.6	-19.9	13.1	3.3	543	<i>Cervus elaphus</i>	tooth	28770	3599 ± 29	15.5	-19.4	5.6	3.3
Ust' Iamnaia	UIA_1977.005	EBA	adult	28767	4137 ± 30	10.6	-19.8	12.1	3.3	452	<i>Cervus elaphus</i>	tooth	28771	3685 ± 30	13.8	-20.2	5.6	3.3
Ust' Iamnaia	UIA_1977.007.02	EBA	subadult	28768/9	4125 ± 21	13.1	-19.9	13.1	3.3	463	<i>Cervus elaphus</i>	tooth	28772	3662 ± 29	12.6	-19.9	5.8	3.3

Table 2 Stable carbon and nitrogen isotope data on modern fish bone collagen from the Upper Lena, with $\delta^{13}\text{C}$ adjusted by +1.5‰ for the fossil fuel effect (raw data from Katzenberg et al. 2012:Table 4; note that the pike sample, E2002.389, is the same specimen that was ^{14}C dated in the present study).

Sample ID	Species	Common name	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	C:N
E2002.351	<i>Brachymystax lenok</i>	lenok	-25.5	10.8	3.0
E2002.352	<i>Brachymystax lenok</i>	lenok	-25.2	11.5	3.1
E2002.353	<i>Brachymystax lenok</i>	lenok	-25.0	11.9	2.8
E2002.389	<i>Esox lucius</i>	northern pike	-22.5	11.2	3.3
E2002.355	<i>Leuciscus baicalensis</i>	dace	-24.1	10.2	3.4
	Average		-24.5 ± 1.2	11.1 ± 0.7	

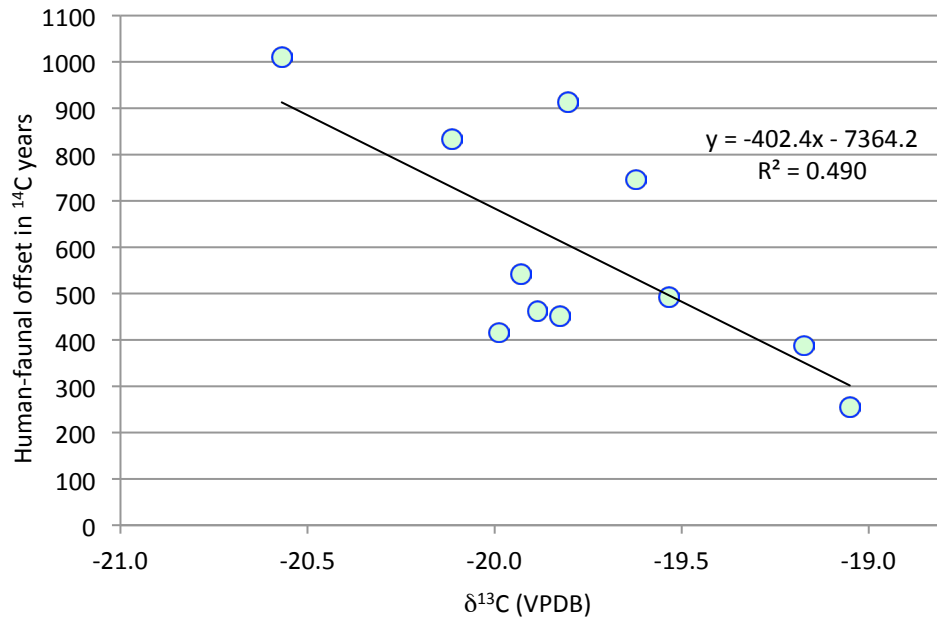


Figure 2 Plot of human bone collagen $\delta^{13}\text{C}$ values against human-faunal offsets in ^{14}C years ($n = 11$)

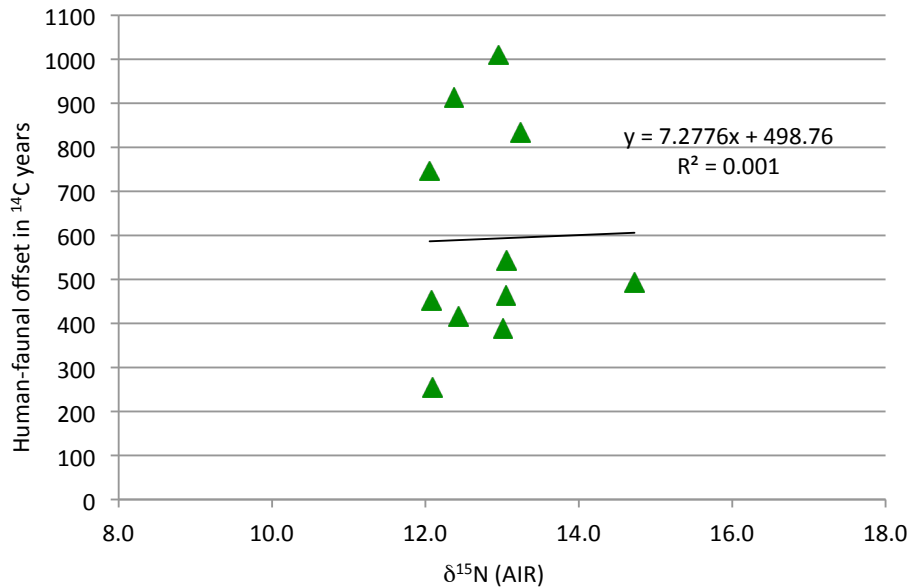


Figure 3 Plot of human bone collagen $\delta^{15}\text{N}$ values against human-faunal offsets in ^{14}C years ($n = 11$)

DISCUSSION

The paired human-fauna dating program for sites along the Upper Lena River demonstrates the existence of a considerable freshwater reservoir offset for all samples. Indeed, the maximum offset of 1010 ^{14}C yr observed in the present study is markedly higher than that of 622 ^{14}C yr found in a recent project focusing on Lake Baikal and the Angara River (the waters of which derive from Baikal) (Bronk Ramsey et al. 2014; Schulting et al. 2014). There is some suggestion that the two sites

located in the northern part of the study area have a larger mean offset (752 ± 249 ^{14}C yr) than the three southern sites (501 ± 204 ^{14}C yr), though this does not attain statistical significance (Student's t test, $t = 1.82$, $p = 0.102$, $df = 9$). It is not possible to meaningfully compare individual sites, since no site in the present study contributed more than three paired dates, as we were aiming to get a broad characterization of the FRE for the Upper Lena as a whole. However, there is a clear impression that the offsets from the same sites are more similar to one another than they are to the overall data set (Table 1).

There is a significantly higher mean offset in the three individuals from the earliest sites (Late Mesolithic and Early Neolithic: 919 ± 88 ^{14}C yr) compared to later sites (Late Neolithic and Early Bronze Age: 470 ± 141 ^{14}C yr) (heteroscedastic Student's t test: $t = 6.32$, $p < 0.000$, $df = 6$). This could suggest that the EN saw greater use of fish resources on the Lena, something that has also been proposed for communities on Baikal and the Angara (Weber et al. 2002:272; Weber and Bettinger 2010). For the Lena, the difference in ^{14}C offsets between the early and late groups is not matched by any significant difference in either $\delta^{15}\text{N}$ (heteroscedastic Student's t test: $t = 0.10$, $p = 0.92$, $df = 8$) or $\delta^{13}\text{C}$ (Mann-Whitney U test, $p = 0.10$) values. The difference in $\delta^{13}\text{C}$ is perhaps suggestive (-20.2 ± 0.4 for the early group vs. -19.6 ± 0.3 for the late group), and it is in the expected direction for higher consumption of freshwater fish, i.e. more negative. However, the lack of any corresponding increase in the $\delta^{15}\text{N}$ values is puzzling. Rather than indicating greater use of fish in the Late Mesolithic and Early Neolithic, it might be proposed that the fish taken from particular locations had incorporated larger amounts of old carbon. Against this, though recognizing that sample numbers are very low, it can be noted that the two LN individuals from Zakuta have higher offsets than the two EN individuals from nearby Turuka. Both sites are immediately alongside the Lena, and so differential access to fish should not be an issue. Alternatively, and as discussed below, it might be that the FRE itself changed over time (cf. Ascough et al. 2010).

Taking the possibility of change in diet and/or FRE effects over time as a cue, some additional patterning is evident when the analysis is restricted to the six individuals from the two EBA sites of the southern group, Ust'-Iamnaia and Makrushino. Not only is the correlation between $\delta^{13}\text{C}$ and ^{14}C offsets considerably stronger ($r^2 = 0.717$, $p = 0.033$), but the inclusion of $\delta^{15}\text{N}$ improves the correlation (adjusted $r^2 = 0.840$, $p = 0.030$) (Table 3). Whether this outcome is due to changes in the FRE over time or to location in the south of the study area is unclear, since the only other sample from the southern group is a single individual from the Late Mesolithic/Early Neolithic site of Popovskii Lug 2, which could be anomalous.

Table 3 Model parameters used in this study.

Regression model	Equation	S	r^2	p	n
Full data set, $\delta^{13}\text{C}$	$-7364.2 - 402.4 (\delta^{13}\text{C})$	183.6	0.490	0.016	11
EBA sites, $\delta^{13}\text{C}$	$-3955.0 - 224.2 (\delta^{13}\text{C})$	59.9	0.717	0.033	6
EBA sites, $\delta^{13}\text{C}$ & $\delta^{15}\text{N}$	$-4289.9 - 211.2 (\delta^{13}\text{C}) + 45.4 (\delta^{15}\text{N})$	40.3	0.840	0.030	6

Source of Old Carbon in the Upper Lena

The lack of any connection between the Upper Lena watershed and the waters of Lake Baikal suggests that the source(s) of old carbon may not be the same. The source of the carbon reservoir in Lake Baikal itself is still unclear, with various proposals including the residence time of the water in the lake (Afanas'ev 1960:Table 55; Kozhov 1963:28; though see Hohmann et al. 1997), the introduction of old CO_2 derived from glacial meltwater (Osipov and Khlystov 2010), and dead carbon

from underwater methane hydrate outgassing (Prokopenko and Williams 2004). Geothermal activity has been suggested as an explanation for FRE noted at the site of Klin Yar in the North Caucasus (Higham et al. 2010; see also Ascough et al. 2010); hot springs are present in the Baikal region and so might also be a factor there. Terrestrial runoff incorporating old carbon from soil organic matter (SOM) presents itself as another possibility, one discussed below in relation to the Lena.

Unlike the great majority of Lake Baikal's catchment, centered to the east and south of the lake and contributing little carbonate to the lake's waters (Colman et al. 1996; Prokopenko et al. 1999), the Upper Lena watershed flows over Lower Paleozoic limestone bedrock, such that its waters are CaCO_3 -saturated (Gordeev and Sidorov 1993; Huh et al. 1998). Alkalinity at the mouth of the Lena is moderately high at $961 \pm 70 \text{ mmol kg}^{-1}$ (Cooper et al. 2008:Table 1), or $\sim 96 \text{ mg CaCO}_3/\text{L}$, but is higher in the river's upper reaches (Pipko et al. 2010). The positive correlation ($r^2 = 0.68$) identified between alkalinity and reservoir offsets in British and Irish lakes suggests that even the more conservative concentration of $96 \text{ mg CaCO}_3/\text{L}$ would equate with an offset of about 700–1000 ^{14}C yr (Keaveney and Reimer 2012:Figure 4), which, as it happens, is close to the observed maximum human-faunal offset of 1010 yr in the present study—though this would require that all the protein in this individual's diet derived from fish or other aquatic species, which is improbable.

Whatever its specific contribution, a geological source offers one possibility for the introduction of old (dead) carbon into the river system. Dissolved inorganic carbon (DIC) can only be incorporated into the foodweb through photosynthesis, either by phytoplankton or algae. However, primary productivity in many rivers is low compared to the input of organic matter derived from terrestrial vegetation and soils (Søballe and Kimmel 1987; Rachold and Hubberten 1999; Lobbes et al. 2000; Bauer and Bianchi 2011:18; Berggren et al. 2015; though see Reynolds and Descy 1996; Thorp and Delong 2002). This would be particularly so for the “black,” organic-rich waters of the Lena, limiting photosynthesis, with total suspended solids (TSS) in the river's upper reaches being on the order of 100 g/m^3 , or 100 mg/L (Telang et al. 1991; cf. Cauwet and Sidorov 1996). As a result, it has been calculated that the autochthonous phytoplankton contribute only some 2% of the average particulate organic matter (POC) in the Lena (Sorokin and Sorokin 1996; Lara et al. 1998; Lobbes et al. 2000). Thus, the great majority of carbon involved in the aquatic foodweb here, as in other north temperate freshwater systems, appears to be of allochthonous, terrestrial origin, assimilated by macroinvertebrate filter feeders and aquatic bacterioplankton (Jansson et al. 2000; Berggren et al. 2015). It remains to account for its depleted ^{14}C content.

Many of the same erosional processes responsible for bringing bedrock carbonate into the river could introduce old soil carbon from the discontinuous permafrost zone that dominates the Lena's headwaters (Pipko et al. 2010; Bezrukova et al. 2014). Most of the research on the Lena and other Russian Arctic rivers has focused on their discharge into the Laptev Sea. Thus, while not directly applicable to the situation in the river's upper reaches, it can be noted that bulk organic carbon in the surface sediments of the mouth of the Lena have been dated to $7500 \pm 60 \text{ }^{14}\text{C}$ yr BP ($0.394 \pm 0.003 \text{ }^{14}\text{C}$ Fm), attributed to the input of old carbon released from permafrost into the river during summer thaws and via bank erosion (Gustafsson et al. 2011:Table 2; see also Raymond and Bauer 2001; Guo et al. 2004; Feng et al. 2013; though see Benner et al. 2004). Speleothem research at Botovskaya Cave in the Upper Lena watershed demonstrates periods of active growth, indicating that temperatures were sufficient to melt the permafrost at various points during the Holocene (Vaks et al. 2013).

The ^{14}C ages of SOM are highly variable, particularly when many meters of permafrost are involved (Wassenaar et al. 1990; Orlova and Panychev 1993). The incorporation of this old carbon could

account for the high degree of variability observed in the ^{14}C offsets in the present study, as well as the limited correlation with $\delta^{13}\text{C}$, though the absence of a stronger correlation with $\delta^{15}\text{N}$ remains puzzling. The age of the terrestrial organic material forming much of the basis of the foodweb would be variable both spatially and temporally, but with similar $\delta^{13}\text{C}$ values to those of the aquatic system. Recent studies have shown that dissolved organic carbon (DOC) derived from permafrost soils is highly biolabile, and indeed may even be preferentially taken up by heterotrophic bacterioplankton (McCallister and del Giorgio 2012; Vonk et al. 2013). The source(s) of old carbon in the Upper Lena river system require further investigation, particularly in terms of understanding the contributions of the various streams and rivers feeding into the Upper Lena, which may help to explain some of the observed variability in ^{14}C offsets (cf. Yu et al. 2007). For present purposes, we have established that the FRE is a substantial and hitherto unrecognized factor to be taken into account when dating prehistoric human remains from the region.

A correlate is that changing climate conditions within the Upper Lena watershed will impact on the extent of the FRE, through changing contributions of both inorganic and organic carbon. While this could conceivably be a factor throughout the Baikal region more generally, its sheer size suggests that Lake Baikal itself may have been buffered to a large extent from changing inputs of old carbon. Following on from the previous discussion, organic carbon is likely to be the more important factor in terms of the both the radiogenic and stable isotope ecology of the river system. It is difficult to translate global climatic patterns (Svensson et al. 2005) to the regional scale, but various studies in the Baikal region have begun to provide a framework for the investigation of links between human culture history and the paleoenvironmental record (White and Bush 2010). While the evidence is not unambiguous, there may be a local manifestation of the global cooling trend termed the Neoglacial Holocene from ~6000 cal BP (Crockford and Frederick 2007), relative to the preceding Holocene climatic optimum, with both higher annual precipitation and temperatures (Tarasov et al. 2007, 2009; Bezrukova et al. 2010, 2014). This could potentially be a factor in the observed lessening of the FRE in the Late Neolithic (commencing ~5700 cal BP) and Early Bronze Age humans in the Upper Lena, through reduced erosion of permafrost, with its sequestered load of old soil carbon. The confounding factor is that people could have simply consumed less fish at this time, as has been suggested on the basis of stable isotope results for Cis-Baikal (Weber et al. 2002, 2011). Complicating matters still further, both environmental and human behavioral factors may have acted in tandem.

The Upper Lena in the Context of Cis-Baikal

The finding of a moderate negative correlation between human $\delta^{13}\text{C}$ values and ^{14}C offsets enables a provisional FRE correction of human bone dates from sites along the Upper Lena as a whole. This seems reasonably robust, though considerably less of the variation in ^{14}C offsets is accounted for than was the case for our previous models for Lake Baikal and the Angara (Bronk Ramsey et al. 2014; Schulting et al. 2014). The separate regression equation for the EBA of the southern Upper Lena group accounts for significantly more variation, though being derived from only six paired dates, some caution is warranted. The small contribution of $\delta^{15}\text{N}$ is surprising, since there is a clear trophic level difference between the values of modern terrestrial large mammals ($5.3 \pm 0.9\text{‰}$) and riverine fish ($11.1 \pm 0.7\text{‰}$) (Weber et al. 2011; Katzenberg et al. 2012). The comparatively low resolution correction given by the overall model will make it difficult to look at the kinds of finer-scale chronological patterning for the Upper Lena region as a whole that are now becoming possible for many other sites of Cis-Baikal (unpublished data). Whether the much more promising equation derived for the EBA of the southern sites can be applied to earlier periods remains to be determined.

The low average $\delta^{13}\text{C}$ of $-19.8 \pm 0.4\text{‰}$ for Upper Lena humans compared to those from the shores of Lake Baikal or along the Angara River supports the lack of any significant contact in terms of

access to the Lake's inshore fish resources, which typically exhibit elevated $\delta^{13}\text{C}$ bone collagen values, averaging about -16‰ (Katzenberg et al. 2012; see also Kiyashko et al. 1998; Yoshii 1999; Weber et al. 2011). However, there are individuals from Lake Baikal with broadly comparable $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values to those of the Upper Lena. They typify what has been termed the game-fish (GF) diet, identified primarily at Early Bronze Age sites on the Little Sea, a microregion of Lake Baikal (Weber and Goriunova 2013). What is particularly intriguing is the presence of two distinct, contemporaneous diets (GF and game-fish-seal, GFS) within the same cemeteries. Strontium isotope analysis has placed the origins of many or even all individuals with GF diets away from the Little Sea, with the most obvious location being the southern reaches of the Upper Lena, some 65 km distant (Scharlotta et al. 2013; Weber and Goriunova 2013). Movement in the reverse direction, from the Little Sea to the Upper Lena, seems to have been rare, but is hinted at by $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data for a very few individuals (Weber et al. 2002; ORAU, unpublished data).

Individuals exhibiting GF diets from the Little Sea sites of Khuzhir-Nuge XIV and Kurma XI featured in our previous regression models, in which $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotope values together accounted for 86% of the variability in ^{14}C offsets (Schulting et al. 2014:Table 6). The current study presents a model for the approximately contemporaneous EBA sites of the southern Upper Lena in which both stable isotopes account for a comparable 84% of the variability in ^{14}C offsets, but with different slope coefficients, and opposite roles for the predictive power of $\delta^{13}\text{C}$ (high in the Upper Lena, low in the Little Sea) and $\delta^{15}\text{N}$ (the reverse). Furthermore, the FRE is significantly higher in the EBA of the Upper Lena than that seen with the GF diet in the Little Sea (432 ± 101 vs. 149 ± 91 ^{14}C yr: Student's t test, $t = 5.29$, $p < 0.000$, $df = 10$) (Schulting et al. 2014:Table 6). For the Upper Lena–Little Sea connection to remain viable, individuals moving from the former to the latter would have needed to significantly change their diets to protein sources with a lower carbon reservoir age, at the same time avoiding the local inshore fishes and seals characteristic of the GFS diet. While this seems improbable, it is also the case that there are potentially many factors at play, for which our current knowledge is limited. Further work is clearly necessary to revisit the previously proposed connections between the Upper Lena and the Little Sea microregions. Although they may still prove to hold, in the light of the new data presented here, the case is perhaps not as compelling as it was, and other possible connections may need to be considered.

Finally, it can be noted that the application of an FRE correction for the dated human remains of Cis-Baikal allows a reconsideration of the poorly known Middle Neolithic (MN) period, as some individuals previously assigned to EN could become younger by some centuries. That being said, ongoing research into this issue so far suggests that very few individuals will be shifted in this way (unpublished data). Conversely, individuals that might have been placed in the MN can now be shown to belong within the Late Neolithic (post-5700 cal BP) once the FRE is taken into account. The two individuals from Zakuta included in this study fall into this category. If not corrected for offsets—of 416 ^{14}C yr in one case and 746 ^{14}C yr in the other—both would date to ~ 6000 cal BP and so be placed in the MN. The mortuary practices of this period are too little known to assign graves to this or later traditions (or indeed, earlier traditions) based on the burial rite (Weber et al. 2010), so that direct dating (with an appropriate FRE correction) will be essential in fleshing out our knowledge of this important transitional period. Overall, however, it seems more likely that taking the Upper Lena's FRE into consideration will affect only the upper EN and lower LN boundaries rather than populate the MN mortuary record.

CONCLUSIONS

The identification of a substantial freshwater ^{14}C offset on human bone dates from prehistoric burials of the Upper Lena raises a number of issues for understanding the region's culture history, and its

links with the hunter-gatherer populations of Cis-Baikal as a whole. Two different regression equations have been calculated, the first using human $\delta^{13}\text{C}$ values for the entire data set ($r^2 = 0.49$) and the second, using both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, limited to the EBA of the southern Upper Lena ($r^2 = 0.84$). Surprisingly, no relationship was found between $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, with the latter exhibiting only a small correlation with ^{14}C offsets, and that restricted to the EBA samples. The small sample size means that these results are perhaps less robust than those previously reported for Lake Baikal and the Angara. Nevertheless, the regression equations presented here are the best currently available means of correcting for the FRE in the Upper Lena watershed. The alternative is to limit ^{14}C dating to terrestrial faunal remains or, where preserved, plant material (cf. Higham et al. 2010), but most graves do not contain appropriate materials. This problem is not unique to Baikal, and other studies have noted difficulties in predicting the FRE, which must be dealt with on a case-by-case basis, and even then may be intractable (Higham et al. 2010; Wood et al. 2013).

An important source of the ^{14}C offset in the Upper Lena is likely to be old carbon incorporated from soils, especially from permafrost, during spring and summer runoff and through bank erosion. This implies that, as is being clearly demonstrated today in the major rivers of Siberia (Raymond and Bauer 2001; Guo et al. 2004; Gustafsson et al. 2011; Feng et al. 2013), climate will have played a large role in determining the FRE in the Lena River in the past. This might have wider application across Cis-Baikal, which would have consequences for previous interpretations of the isotopic differences both within and between Early Neolithic and Late Neolithic/Early Bronze Age populations. Thus, there are a number of avenues to explore in order to improve our understanding of the past dynamics and isotope ecology of both the Upper Lena watershed and the Cis-Baikal region as a whole.

ACKNOWLEDGMENTS

We thank V M Vetrov (Irkutsk Pedagogical University) for providing samples from Makrushino and Ust'-Iamnaia. All other samples are from the excavations of V I Bazaliiskii. Thanks also to the journal's anonymous reviewers for their very useful comments, and to the organizers of the Radiocarbon and Diet meeting in Kiel, which presented the opportunity to discuss a number of issues that have directly or indirectly informed this paper. This research was supported by the Social Sciences and Humanities Research Council of Canada (Major Collaborative Research Initiative grant No. 412-2011-1001).

REFERENCES

- Afanas'ev AN. 1960. Vodnyi balans oz. Baikal. *Obshchie morphometricheskie dannye kotloviny Baikala. Trudy Baikal'skoi limnologicheskoi stantsii*, Volume XVIII. p 155–241.
- Ascough PL, Cook GT, Church MJ, Dunbar E, Einarsson A, 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(3):1098–112.
- Bauer JE, Bianchi TS. 2011. Dissolved organic carbon cycling and transformation. In: Wolanski E, McLusky DS, editors. *Treatise on Estuarine and Coastal Science, Volume 5*. Waltham: Academic Press. p 7–67.
- Benner R, Benitez-Nelson B, Kaiser K, Amo RMW. 2004. Export of young terrigenous dissolved organic carbon from rivers to the Arctic Ocean. *Geophysical Research Letters* 31(5):L05305.
- Berggren M, Sponseller RA, Alves Soares AR, Bergstrom A-K. 2015. Toward an ecologically meaningful view of resource stoichiometry in DOM-dominated aquatic systems. *Journal of Plankton Research* 37(3):489–99.
- Bezrukova EV, Tarasov PE, Solovieva N, Krivonogov SK, Riedel F. 2010. Last glacial—interglacial vegetation and environmental dynamics in southern Siberia: chronology, forcing and feedbacks. *Palaeogeography, Palaeoclimatology, Palaeoecology* 296(1–2):185–98.
- Bezrukova EV, Belov AV, Letunova PP, Kulagina NV. 2014. The response of the environment of the Angara–Lena Plateau to global climate change in the Holocene. *Russian Geology and Geophysics* 55:463–71.
- Bocherens H, Drucker D. 2003. Trophic level isotopic enrichments for carbon and nitrogen in collagen: case studies from recent and ancient terrestrial eco-

- systems. *International Journal of Osteoarchaeology* 13(1–2):46–53.
- Brock F, Bronk Ramsey C, Higham TFG. 2007. Quality assurance of ultrafiltered bone dating. *Radiocarbon* 49(2):189–92.
- Brock F, Higham TFG, Ditchfield P, Bronk Ramsey C. 2010. Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU). *Radiocarbon* 52(1):102–12.
- Bronk Ramsey C, Lee S. 2013. Recent and planned developments of the program OxCal. *Radiocarbon* 55(2–3):720–30.
- Bronk Ramsey C, Schulting RJ, Goriunova OI, Bazaliiskii VI, Weber AW. 2014. Analyzing radiocarbon reservoir offsets through stable nitrogen isotopes and Bayesian modeling: a case study using paired human and faunal remains from the Cis-Baikal region, Siberia. *Radiocarbon* 56(2):789–99.
- Cauwet G, Sidorov IS. 1996. The biogeochemistry of the Lena river: organic carbon and nutrients distribution. *Marine Chemistry* 53(3–4):211–27.
- Colman SM, Jones GA, Rubin M, King JW, Pecks JA, Orens JH. 1996. AMS radiocarbon analyses from Lake Baikal, Siberia: challenges of dating sediments from a large, oligotrophic lake. *Quaternary Science Reviews* 15(7):669–84.
- Cooper LW, McClelland JW, Holmes RM, Raymond PA, Gibson JJ, Guay CK, Peterson BJ. 2008. Flow-weighted values of runoff tracers ($\delta^{18}\text{O}$, DOC, Ba, alkalinity) from the six largest Arctic rivers. *Geophysical Research Letters* 35:L18606.
- Crockford SJ, Frederick SG. 2007. Sea ice expansion in the Bering Sea during the Neoglacial: evidence from archaeozoology. *The Holocene* 17(6):699–706.
- DeNiro MJ. 1985. Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317(6040):806–9.
- Feng X, Vonk JE, van Dongen BE, Gustafsson Ö, Semiletov IP, Dudarev OV, Wang Z, Montluçon DB, Wacker L, Eglinton TI. 2013. Differential mobilization of terrestrial carbon pools in Eurasian Arctic river basins. *Proceedings of the National Academy of Sciences of the USA* 110(335):14,168–73.
- Gordeev VV, Sidorov IS. 1993. Concentrations of major elements and their outflow into the Laptev Sea by the Lena River. *Marine Chemistry* 43(1–4):33–45.
- Gruber N, Keeling CD, Bacastow RB, Guenther PR, Luiker TJ, Wahlen M, Meijer HAJ, Mook WG, Stocker TF. 1999. Spatiotemporal patterns of carbon-13 in the global surface oceans and the oceanic Suess effect. *Global Biogeochemical Cycles* 13(2):307–35.
- Guo L, Semiletov I, Gustafsson Ö, Ingri J, Andersson P, Dudarev O, White D. 2004. Characterization of Siberian Arctic coastal sediments: implications for terrestrial organic carbon export. *Global Biogeochemical Cycles* 18(1):GB1036.
- Gustafsson Ö, van Dongen BE, Vonk JE, Dudarev OV, Semiletov IP. 2011. Widespread release of old carbon across the Siberian Arctic echoed by its large rivers. *Biogeosciences* 8:1737–43.
- Hedges REM, Reynard LM. 2007. Nitrogen isotopes and the trophic level of humans in archaeology. *Journal of Archaeological Science* 34(8):1240–51.
- Higham TFG, Warren R, Belinskij A, Härke H, Wood R. 2010. Radiocarbon dating, stable isotope analysis, and diet-derived offsets in ages from the Klin Yar site, Russian North Caucasus. *Radiocarbon* 52(2):653–70.
- Hohmann R, Kipfer R, Peeters F, Piepke G, Imboden DM, Shimarev MN. 1997. Deep-water renewal in Lake Baikal. *Limnology and Oceanography* 42(5):841–55.
- Huh Y, Tsoi M-Y, Zaitsev A, Edmond JM. 1998. The fluvial geochemistry of the rivers of Eastern Siberia: I. Tributaries of the Lena River draining the sedimentary platform of the Siberian Craton. *Geochimica et Cosmochimica Acta* 62(10):1657–76.
- Jansson M, Bergström A-K, Blomqvist P, Drakare S. 2000. Allochthonous organic carbon and phytoplankton/bacterioplankton production relationships in lakes. *Ecology* 81(11):3250–5.
- Katzenberg MA, Weber A. 1999. Stable isotope ecology and palaeodiet in the Lake Baikal region of Siberia. *Journal of Archaeological Science* 26(6):651–9.
- Katzenberg MA, Goriunova OI, Weber A. 2009. Paleodiet reconstruction of Early Bronze Age Siberians from the site of Khuzhir-Nuge XIV, Lake Baikal. *Journal of Archaeological Science* 36(3):663–74.
- Katzenberg MA, Bazaliiskii VI, Goriunova OI, Savel'ev N, Weber AW. 2010. Diet reconstruction of prehistoric hunter-gatherers in the Lake Baikal region. In: Weber AW, Katzenberg MA, Schurr TG, editors. *Prehistoric Hunter-Gatherers of the Baikal Region, Siberia*. Philadelphia: University of Pennsylvania Press. p 175–91.
- Katzenberg MA, McKenzie HG, Losey RJ, Goriunova OI, Weber A. 2012. Prehistoric dietary adaptations among hunter-fisher-gatherers from the Little Sea of Lake Baikal, Siberia, Russian Federation. *Journal of Archaeological Science* 39(8):2612–26.
- Keaveney EM, Reimer PJ. 2012. Understanding the variability in freshwater radiocarbon reservoir offsets: a cautionary tale. *Journal of Archaeological Science* 39(5):1306–16.
- Keeling CD. 1979. The Suess effect: ^{13}C - ^{14}C interrelations. *Environment International* 2(4–6):229–300.
- Kiyashko SI, Richard P, Chandler T, Kozlova TA, Williams DF. 1998. Stable carbon isotope ratios differentiate autotrophs supporting animal diversity in Lake Baikal. *Comptes Rendus Biologies* 321(6):509–16.
- Kozhov M. 1963. *Lake Baikal and Its Life*. The Hague: Dr. W. Junk.
- Lara RJ, Rachold V, Kattner G, Hubberten H-W, Guggenberger G, Skoog A, Thomas DN. 1998. Dissolved organic matter and nutrients in the Lena River, Siberian Arctic: characteristics and distribution. *Marine Chemistry* 59(3–4):301–9.
- Lobbies JM, Fitznar HP, Kattner G. 2000. Biogeo-

- chemical characteristics of dissolved and particulate organic matter in Russian rivers entering the Arctic Ocean. *Geochimica et Cosmochimica Acta* 64(17):2973–83.
- McCallister SL, del Giorgio PA. 2012. Evidence for the respiration of ancient terrestrial organic C in northern temperate lakes and streams. *Proceedings of the National Academy of Sciences of the USA* 109(42):16,963–8.
- Minagawa M, Wada E. 1984. Stepwise enrichment of ^{15}N along food chains: further evidence and the relation between $\delta^{15}\text{N}$ and animal age. *Geochimica et Cosmochimica Acta* 48(5):1135–40.
- Nomokonova T, Losey RJ, Goriunova OI, Weber AW. 2013. A freshwater old carbon offset in Lake Baikal, Siberia and problems with the radiocarbon dating of archaeological sediments: evidence from the Sagan-Zaba II site. *Quaternary International* 290–291:110–25.
- Orlova LA, Panychev VA. 1993. The reliability of radiocarbon dating buried soils. *Radiocarbon* 35(3):369–77.
- Osipov EY, Khlystov OM. 2010. Glaciers and meltwater flux to Lake Baikal during the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* 294(1):4–15.
- Pipko II, Pugach SP, Dudarev OV, Charkin AN, Semiletov IP. 2010. Carbonate parameters of the Lena River: characteristics and distribution. *Geochemistry International* 48(11):1131–7.
- Prokopenko AA, Williams DF. 2004. Deglacial methane emission signals in the carbon isotopic record of Lake Baikal. *Earth and Planetary Science Letters* 218(1–2):135–47.
- Prokopenko AA, Williams DF, Karabanov EB, Khursevich GK. 1999. Response of Lake Baikal ecosystem to climate forcing and $p\text{CO}_2$ change over the last glacial/interglacial transition. *Earth and Planetary Science Letters* 172(3–4):239–53.
- Rachold V, Hubberten H-W. 1999. Carbon isotope composition of particulate organic material in East Siberian rivers. In: Kassens H, Bauch HA, Dmitrenko I, Eicken H, Melles M, Thiede J, Timokhov L, editors. *Land-Ocean Systems in the Siberian Arctic*. Berlin: Springer-Verlag. p 223–38.
- Raymond PA, Bauer JE. 2001. Riverine export of aged terrestrial organic matter to the North Atlantic Ocean. *Nature* 409(6819):497–500.
- Reynolds CS, Descy J-P. 1996. The production, biomass and structure of phytoplankton in large rivers. *Archives of Hydrobiology* 113:161–87.
- Scharlotta I, Goriunova OI, Weber A. 2013. Micro-sampling of human bones for mobility studies: diagenetic impacts and potentials for elemental and isotopic research. *Journal of Archaeological Science* 40(12):4509–27.
- Schulting RJ, Bronk Ramsey C, Goriunova OI, Bazaliskii VI, Weber A. 2014. Freshwater reservoir offsets investigated through paired human-faunal ^{14}C dating and stable carbon and nitrogen isotope analysis at Lake Baikal, Siberia. *Radiocarbon* 56(3):991–1008.
- Søballe DM, Kimmel BL. 1987. A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes, and impoundments. *Ecology* 68(6):1943–54.
- Sorokin YI, Sorokin PY. 1996. Plankton and primary production in the Lena River estuary and in the south-eastern Laptev Sea. *Estuarine, Coastal and Shelf Science* 43(4):399–418.
- Stenhouse MJ, Baxter MS. 1979. The uptake of bomb ^{14}C in humans. In: Berger R, Suess HE, editors. *Proceedings of the 9th International Conference on Radiocarbon Dating*. Los Angeles: University of California Press. p 324–41.
- Svensson A, Andersen KK, Bigler M, Clausen HB, Dahl-Jensen D, Davies SM, Johnsen SJ, Muscheler R, Parrenin F, Rasmussen SO, Röthlisberger R, Seierstad I, Steffensen JP, Vinther BM. 2008. A 60 000 year Greenland stratigraphic ice core chronology. *Climate of the Past* 4(1):47–57.
- Tarasov P, Bezrukova E, Karabanov E, Nakagawa T, Wagner M, Kulagina N, Letunova P, Abzaeva A, Granoszewski W, Riedel F. 2007. Vegetation and climate dynamics during the Holocene and Eemian interglacials derived from Lake Baikal pollen records. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252(3–4):440–57.
- Tarasov PE, Bezrukova EV, Krivonogov SK. 2009. Late Glacial and Holocene changes in vegetation cover and climate in southern Siberia derived from a 15 kyr long pollen record from Lake Kotokel. *Climate of the Past* 5(3):285–95.
- Telang SA, Pocklington R, Naidu AS, Romankevich EA, Giletsen II, Gladyshev MI. 1991. Carbon and mineral transport in major North American, Russian Arctic, and Siberian rivers: the St Lawrence, the Mackenzie, the Yukon, the Arctic Alaskan rivers, the Arctic Basin rivers in the Soviet Union, and the Yenisei. In: Degens ET, Kempe S, Richey JE, editors. *Biogeochemistry of Major World Rivers*. Chichester: John Wiley. p 75–104.
- Thorp JH, Delong MD. 2002. Dominance of autochthonous autotrophic carbon in food webs of heterotrophic rivers. *Oikos* 96(3):543–50.
- Uno KT, Quade J, Fisher DC, Wittemyer G, Douglas-Hamilton I, Andanje S, Omondi P, Litoroh M, Cerling TE. 2013. Bomb-curve radiocarbon measurement of recent biologic tissues and applications to wildlife forensics and stable isotope (paleo)ecology. *Proceedings of the National Academy of Sciences of the USA* 110(29):11,736–41.
- Vaks A, Gutareva OS, Breitenbach SFM, Avirmed E, Mason AJ, Thomas AL, Osinzev AV, Kononov AM, Henderson GM. 2013. Speleothems reveal 500,000-year history of Siberian permafrost. *Science* 340(6129):183–6.
- van Klinken GJ. 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science* 26(6):687–95.
- Vonk JE, Mann PJ, Davydov S, Davydova A, Spencer

- RGM, Schade J, Sobczak WV, Zimov N, Zimov S, Bulygina E, Eglinton TI, Holmes RM. 2013. High biolability of ancient permafrost carbon upon thaw. *Geophysical Research Letters* 40(11):2689–93.
- Wassenaar LI, Aravena R, Fritz P, Barker J. 1990. Isotopic composition (^{13}C , ^{14}C , ^2H) and geochemistry of aquatic humic substances from groundwater. *Organic Geochemistry* 15(4):383–96.
- Waters-Rist AL, Bazaliiski VI, Weber A, Katzenberg MA. 2011. Infant and child diet in Neolithic hunter-fisher-gatherers from Cis-Baikal, Siberia: intra-long bone stable nitrogen and carbon isotope ratios. *American Journal of Physical Anthropology* 146(2):225–41.
- Weber AW, Bettinger RL. 2010. Middle Holocene hunter-gatherers of Cis-Baikal, Siberia: an overview for the new century. *Journal of Anthropological Archaeology* 29(4):491–506.
- Weber AW, Goriunova OI. 2013. Hunter-gatherer migrations, mobility and social relations: a case study from the Bronze Age Baikal region, Siberia. *Journal of Anthropological Archaeology* 32(3):330–46.
- Weber AW, Link DW, Katzenberg MA. 2002. Hunter-gatherer culture change and continuity in the Middle Holocene of the Cis-Baikal, Siberia. *Journal of Anthropological Archaeology* 21(2):230–99.
- Weber AW, McKenzie H, Beukens R. 2010. Radiocarbon dating of Middle Holocene cultural history in Cis-Baikal. In: Weber AW, Katzenberg MA, Schurr TG, editors. *Prehistoric Hunter-Gatherers of the Baikal Region, Siberia*. Philadelphia: University of Pennsylvania Press. p 27–49.
- Weber AW, White D, Bazaliiskii VI, Goriunova OI, Savel'ev NA, Katzenberg MA. 2011. Hunter-gatherer foraging ranges, migrations, and travel in the middle Holocene Baikal region of Siberia: insights from carbon and nitrogen stable isotope signatures. *Journal of Anthropological Archaeology* 30(4):523–48.
- Weber AW, Goriunova OI, McKenzie HG, Lieverse AR, editors. 2012. *Kurma XI, a Middle Holocene Hunter-Gatherer Cemetery on Lake Baikal*. Edmonton: Canadian Circumpolar Institute Press.
- White D, Bush A. 2010. Holocene climate, environmental change, and Neolithic biocultural discontinuity in the Baikal region. In: Weber AW, Katzenberg MA, Schurr TG, editors. *Prehistoric Hunter-Gatherers of the Baikal Region, Siberia*. Philadelphia: University of Pennsylvania Press. p 1–26.
- Wood RE, Higham T, Buzilova A, Surorov A, Heinemeier J, Olsen J. 2013. Freshwater radiocarbon reservoir effects at the burial ground of Minino, northwest Russia. *Radiocarbon* 55(1):163–77.
- Yoshii K. 1999. Stable isotope analysis of benthic organisms in Lake Baikal. *Hydrobiologia* 411:145–59.
- Yu S-Y, Shen J, Colman SM. 2007. Modeling the radiocarbon reservoir effect in lacustrine systems. *Radiocarbon* 49(3):1241–54.