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POTENTIAL FRESHWATER RESERVOIR EFFECTS IN A NEOLITHIC SHELL MIDDEN AT RIŅŅUKALNS, LATVIA

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ABSTRACT. Riņņukalns is the only known prehistoric shell midden in the eastern Baltic, and is one of the few middens in northern Europe consisting mainly of freshwater mussel shells. Situated on the Salaca River at the outlet of Lake Burtnieks, in northeastern Latvia, the site was originally excavated in the 1870s, and reinvestigated several times over the following decades. A new excavation in 2011 showed that part of the midden remained intact. The new exposure, dated to the later 4th millennium cal BC, yielded rich fishbone and mollusk shell assemblages, herbivore, human and bird bones, and a wide range of artifacts typical of a subsistence economy based on fishing, hunting, and gathering. Human remains from burials excavated in the 1870s were also located in archives. The co-occurrence at Riņņukalns of human remains with a broad range of terrestrial and aquatic food remains provides an ideal setting to study freshwater reservoir effects and other isotopic signals of diet and mobility. The extent of ^{14}C depletion in local freshwater resources is an essential parameter for such studies; on the basis of ^{14}C ages of modern and paleoenvironmental samples, we estimate that the applicable reservoir age in Lake Burtnieks is in the order of 800–900 ^{14}C yr.

INTRODUCTION

Riņņukalns, in northern Latvia (Figure 1), is the only known Stone Age shell midden in the eastern Baltic, a well-stratified accumulation consisting mainly of freshwater mussels. First excavated in the 1870s, and sporadically re-excavated until the 1940s, it produced ceramics, bone tools, and some art objects. A Medieval-early modern cemetery cut into the midden, but prehistoric burials sealed by the midden were also reported (Sievers 1875, 1877; Sommer 1884; Šturms 1927). Despite its uniqueness and importance, the site attracted no further research interest for a long time, on the assumption that it had been almost completely destroyed in the course of the extensive 19th century excavations. Almost 70 yr after the last excavation, the Institute of Latvian History, Latvia, and the Centre for Baltic and Scandinavian Archaeology, Germany decided to reinvestigate the site. An excavation in 2011 demonstrated that significant parts of the midden are still preserved intact, and yielded rich assemblages of fish bones and freshwater shells, as well as herbivore, human, and bird bones (Bērziņš et al., forthcoming).

The co-occurrence of burials with *in situ* remains of a wide range of dietary species provides an excellent opportunity to use isotopic ratios to reconstruct human diet and mobility, as long as the different food resources and their habitats have distinct isotopic signals. Stable isotope (δ^{13}C and δ^{15}N) data from human and animal bones and teeth found at Zvejnieki, a prehistoric cemetery on the opposite shore of Lake Burtnieks, ~5 km from Riņņukalns (Figure 1), show clear patterns related to the consumption of terrestrial, marine and freshwater food resources (Eriksson 2006; Eriksson and Lidén 2013). We argue that if the relative dates of samples are tightly constrained by archaeological evidence, ^{14}C ages, particularly of prehistoric human remains, can also provide information about residential and dietary habits, because of variation in ^{14}C depletion between aquatic ecosystems. Conversely, without reliable estimates of ^{14}C depletion in aquatic food resources, ^{14}C dating may produce a misleading absolute chronology for prehistoric human remains and associated artifacts. This article proposes a baseline reservoir age for local freshwater, relevant to the period of occupation at Riņņukalns.

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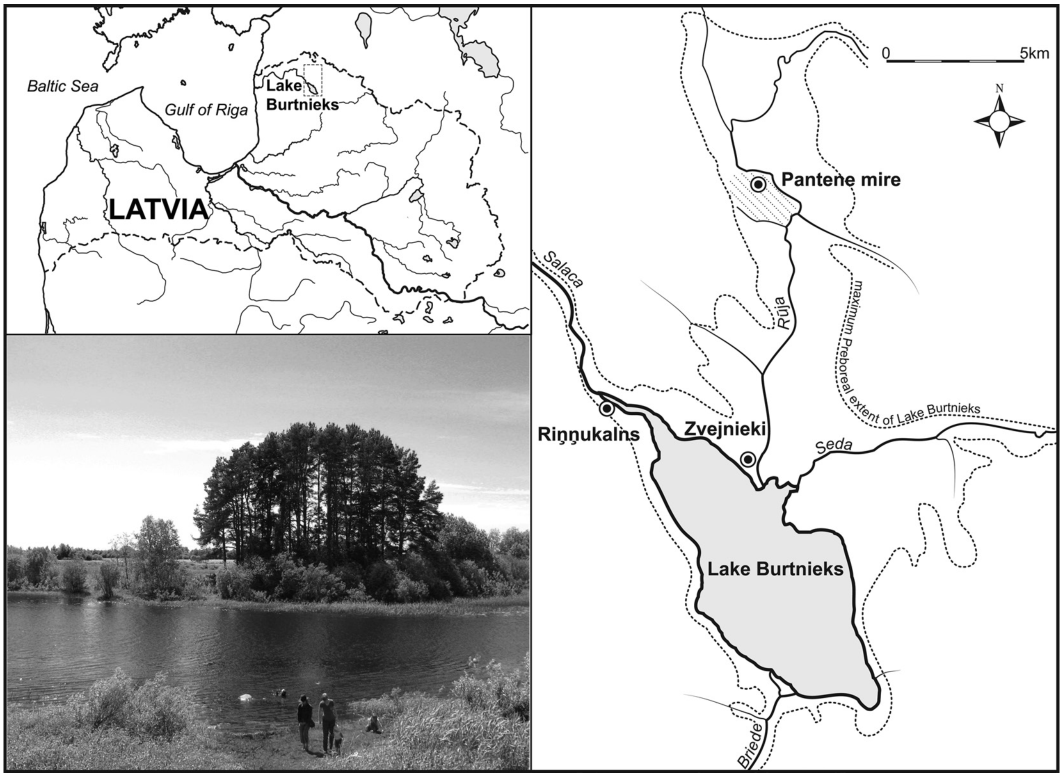

Figure 1 Maps of Latvia and the Lake Burtnieks basin, showing sites mentioned in the text, and the present and Preboreal extent of the lake (after Eberhards 2006). Photo: outlet of Lake Burtnieks at Riņņukalns; the shell midden is under the pine trees.

BACKGROUND

(a) Hydrological Setting

Lake Burtnieks, which lies 40 m above sea level, covers ~40 km^2 and is fed by several small rivers, draining ~2200 km^2 of undulating farmland, forest, and bog. The lake water has an average depth of only 2.4 m, is not stratified, and its residence time is minimal (<3 months); alkalinity was relatively constant at ~3–4 mmol/L (~150–200 mg $CaCO_3$/L) from 1954 to 1998 (Kļaviņš et al. 2001; Lyulko et al. 2001). Bedrock in the catchment consists of Devonian sandstone and siltstone, overlain by 10–20 m of glacial deposits containing reworked boulders and pebbles, including carbonaceous rocks. Following deglaciation, many of the carbonaceous rocks were dissolved by groundwater, and then reprecipitated as calcareous tufa (“freshwater lime”) in the newly formed Lake Burtnieks and many smaller glacial lakes in the Burtnieks catchment, most of which are now overgrown with peat (Eberhards 2006). The present surface area of Lake Burtnieks is only 30% of its maximum extent in the Preboreal (Figure 1), but the location of its outlet, the Salaca River at Riņņukalns, is unlikely to have changed over the course of the Holocene. The Salaca flows directly into the Baltic, 95 km downstream.

(b) Archaeological Setting

The 2011 excavation sampled an area of the midden dated to the later 4th millennium cal BC, both by the presence of decorated pottery attributed to the Middle Neolithic, and by a series of ^{14}C dates on terrestrial herbivores (aurochsen, wild boar) and single fragments of short-lived charcoal, which imply that the excavated layers were deposited very rapidly (Bērziņš et al., forthcoming). Typical Comb Ware pottery from the black soil layer beneath the midden would normally be attributed to the late 5th or early 4th millennium cal BC. Late Mesolithic and early 3rd millennium bone tools have also been recovered, from less secure contexts. In Latvia, the term Neolithic implies the use of pottery, not a subsistence economy based on plant and animal domesticates, and it is thought that wild food resources, including fish and mollusks, constituted the basis of human diet throughout the prehistoric occupation of Riņņukalns.

Two disarticulated human bones found in 2011 have been ^{14}C dated: a late Medieval neonate humerus, from the interface between intact midden layers and the backfill of an earlier excavation trench, and a juvenile maxilla in an undisturbed midden layer. The ^{14}C age of the latter bone dates it to the 4th millennium cal BC, and stable isotope values ($\delta^{15}N$ 12.0‰, $\delta^{13}C$ –24.9‰) suggest he or she regularly consumed freshwater food resources—not surprisingly, as the matrix of the midden consists mainly of freshwater fish bones and mussel shells. More than 2000 fish bones from the midden layers have now been identified, providing an indication of which taxa were consumed regularly: cyprinids, perch, and eel (Bērziņš et al., forthcoming).

RADIOCARBON SAMPLES

(a) Modern Samples

In the late 19th century, the Salaca riverbed in front of Riņņukalns was largely free of mud (Sievers 1877), but a thick layer of mud covered the central lake floor, beginning 0.25–0.5 km from the shore (Sommer 1880). The riverbed next to the midden is now covered by up to 0.5 m of organic-rich mud. This is probably a result of eutrophication due to excessive application of chemical fertilizers, which may have affected isotopic baseline values in aquatic biota, and perhaps the concentration of dissolved inorganic carbonate (DIC). Recorded use of fertilizers in Latvia fell dramatically after 1990 (Kļaviņš et al. 2001), but the applicability of modern data to archaeological questions remains uncertain. Nevertheless, three modern samples were dated: the flesh and shell of a live mussel, and DIC in shallow river water from the same location (Table 1).

There is a rich molluscan fauna in the riverbed mud, now dominated by invasive zebra mussels (*Dreissena polymorpha*). The main bivalve taxon in the shell midden is *Unio* sp. (some fragments being identifiable as *U. tumidus*, the swollen river mussel, and *U. pictorum*, the painter's mussel), complemented by *Anodonta* sp. (Rudzīte et al. 2012). A live duck mussel (*Anodonta anatina*) was collected from the riverbed mud, ~20 m from the midden, in August 2011. The flesh and the outermost 3–4 mm of the shell were sampled, in order to extract carbon assimilated at about the same time (cf. Aldridge 1999). It was assumed that carbon in the flesh was derived mainly from carbon photosynthesized by phytoplankton, and metabolized by the mussel, in spring-summer 2011, while shell carbonate was precipitated from DIC over a similar period.

The shell ^{14}C age should therefore be comparable to the DIC ^{14}C age, as records indicate little seasonal variation in the flow and mineral content of Salaca River water, after the spring snowmelt (Kļaviņš et al. 2001), so that DIC ^{14}C age probably changes little over the course of one growing season. Stable isotope studies suggest that metabolic processes play an important role in shell formation, however (Geist et al. 2005; McConnaughey and Gillikin 2008), which means that the shell ^{14}C age can also be influenced by the mussel's diet. In ^{14}C terms, a mussel's flesh can be older or younger than its shell if it consumes dissolved or particulate organic carbon (DOC/POC) ultimately derived from relict terrestrial vegetation (such as peat bogs) or contemporary terrestrial sources

Table 1 Radiocarbon results from modern samples, collected in August 2011 at Riņņukalns.

Lab nr	Identification		AMS $\delta^{13}C$ (‰)	Corrected ^{14}C concentration ($F^{14}C$)[a]	Conventional ^{14}C age (BP)	Apparent ^{14}C age (BP)[d]
KIA-45725[b]	Dissolved inorganic carbonate (DIC)		−6.65 ± 0.27	0.9263 ± 0.0032[b]	615 ± 25	891 ± 25
KIA-45726	Freshwater mussel (*Anodonta sp.*)	Shell	−9.05 ± 0.60	0.9276 ± 0.0027[c]	604 ± 23	880 ± 23
KIA-45727		Tissue	−30.34 ± 0.82	0.9272 ± 0.0025[c]	607 ± 22	884 ± 22
			−31.26 ± 0.10	0.9441 ± 0.0029[b]	462 ± 25	738 ± 25

[a]$F^{14}C$ corrected for natural fractionation using AMS $\delta^{13}C$ values, as $\delta^{13}C$ values for KIA-45727 are consistent, and KIA-45726 AMS $\delta^{13}C$ appears reasonable, given the DIC $\delta^{13}C$ and the tendency of shell $\delta^{13}C$ to be slightly depleted with respect to DIC in unionids (Dettman et al. 1999).
[b]Pretreated and measured by AMS at the Leibniz Labor für Altersbestimmung, Kiel.
[c]Pretreated at the Leibniz Labor für Altersbestimmung, Kiel; graphitized and measured at Accium BioSciences, Seattle (KIA-45726: 1225–099; KIA-45727: 1225–083).
[d]Conventional ^{14}C age recalculated using a baseline of 1.035 $F^{14}C$, estimated ^{14}C activity of atmospheric CO_2 in mid-2011 (see text).

Table 2 Radiocarbon results from paleoenvironmental samples, from a core collected in November 2011 at Pantene mire, north of Lake Burtnieks (Figure 1). Macrofossils were extracted and identified following the methods described in Ozola et al. (2010).

Depth	Sample	Lab nr	Material dated (bulked seeds, dry weight)	AMS $\delta^{13}C$ (‰)	Corrected ^{14}C concentration ($F^{14}C$)	Conventional ^{14}C age (BP)	Calibrated date (95% confidence)[§]
160–165 cm	Submerged	KIA-47068	*Potamogeton perfoliatus* (9.2 mg), *Najas marina* (0.1 mg)	−26.60 ± 0.90	0.4598 ± 0.0016[a]	6297 ± 29	
				−22.18 ± 0.26	0.4395 ± 0.0017[b]	6603 ± 31	*
	Emerged	KIA-47071	*Scirpus lacustris* (21 mg)	−18.27 ± 0.59	0.4914 ± 0.0019[a]	5708 ± 31	
				−25.89 ± 0.20	0.4874 ± 0.0019[b]	5758 ± 32	4710–4520 cal BC
165–170 cm	Submerged	KIA-47069	*P. perfoliatus* (3.8 mg), *Najas marina* (5.0 mg)	−20.74 ± 0.84	0.4271 ± 0.0016[a]	6833 ± 30	*
	Emerged	KIA-47072	*S. lacustris* (14 mg)	−25.40 ± 1.30	0.4784 ± 0.0018[a]	5923 ± 31	
				−24.79 ± 0.30	0.4808 ± 0.0018[b]	5882 ± 31	4830–4690 cal BC
170–175 cm	Submerged	KIA-47070	*P. perfoliatus* (4.4 mg), *N. marina* (1.6 mg), *N. flexilis* (1.0 mg), *Ceratophyllum submersum* (2.2 mg)	−37.56 ± 0.92	0.4333 ± 0.0014[a]	6718 ± 26	*
	Emerged	KIA-47073	*Scirpus lacustris* (17 mg)	−16.20 ± 0.83	0.4888 ± 0.0018[a]	5750 ± 29	
				−26.56 ± 0.24	0.4770 ± 0.0023[b]	5937 ± 39	4940–4720 cal BC

[a]Pretreated at the Leibniz Labor für Altersbestimmung, Kiel; graphitized and measured at Accium BioSciences, Seattle (KIA-47068: 1225–092; KIA-47071: 1225–094; KIA-47069: 1225–023; KIA-47072: 1225–095; KIA-47070: 1225–093; KIA-47073: 1225–096); fractionation-corrected ^{14}C concentration ($F^{14}C$) calculated using $\delta^{13}C = -25$‰.
[b]Pretreated and measured by AMS at the Leibniz Labor für Altersbestimmung, Kiel; fractionation-corrected ^{14}C concentration ($F^{14}C$) calculated using the AMS $\delta^{13}C$ value.
[§]Calibrated using IntCal09 (Reimer et al. 2009) and OxCal v 4.2 (Bronk Ramsey 2009; intercept method, single floruit rounded outwards to decadal endpoints).
*Calibration not possible without reservoir-effect correction.

(such as manure). Such organic carbon inputs may be more seasonally variable, and less relevant to prehistoric conditions, than DIC and shell ^{14}C ages. Nevertheless, it is carbon from the flesh of mollusks, not from their shells, which enters the food chain, so it is important to assess whether there may be large ^{14}C-age discrepancies between these tissues (Fernandes et al. 2012).

The shell sample was bleached with 0.5 mL 30% H_2O_2 for 15 min in an ultrasonic bath, rinsed in demineralized water and dried at 60°C. The cleaned shell was dissolved in H_3PO_4 and the CO_2 given off was trapped cryogenically for dating. The mussel flesh was simply washed in demineralized water and freeze-dried in preparation for combustion. A glass 1.0-L collection bottle was rinsed repeatedly in the river water, then filled completely and dosed with $HgCl_2$ to poison any microorganisms, and refrigerated before further processing. In the laboratory, a 100-mL sample was filtered through a 0.2-µm aperture membrane and acidified. The evolved CO_2 was trapped cryogenically for dating.

(b) Paleoenvironmental Samples

To estimate the reservoir age in lake water in the mid-Holocene, three pairs of plant macrofossil samples were selected from successive 5-cm slices of a sediment core, collected in the Pantene mire, north of the lake, in November 2011 (Figure 1). This particular core is unpublished, but a comparable core from the same site is described by Ozola et al. (2010). In the sampled section of the core, the sediment is *gyttja*, which formed when the coring site was within Lake Burtnieks, but close to the former shoreline, as shown by the abundance of macrofossils from both underwater and littoral plants. Each pair included an "emerged" sample of common club-rush (*Scirpus [Schoenoplectus] lacustris*) seeds, and a "submerged" sample, of seeds from species that photosynthesize underwater (Table 2). If we assume that the macrofossils within each 5-cm slice are all the same calendar age, the differences in ^{14}C ages between the submerged and emerged samples should correspond to the reservoir age at the date of sedimentation (e.g. Sensuła et al. 2006). It is possible, however, that some of the submerged plants reached the surface and began to photosynthesize atmospheric CO_2, in which case the real reservoir age may have been greater than the difference in ^{14}C ages between samples.

From the identified macrofossils in each level, a sufficient number of seeds was selected to yield enough carbon for a ^{14}C measurement (Table 2). Samples were processed by a simple acid-base-acid extraction with 1% HCl, 1% NaOH at 60°C, and again 1% HCl, giving an "alkali residue fraction," which was sealed in a quartz tube with CuO and silver wire for combustion.

RESULTS

All samples were pretreated at the Leibniz-Labor für Altersbestimmung und Isotopenforschung, Kiel, but to meet reporting deadlines, some of the extracts were sealed and sent to a collaborating laboratory for combustion (if necessary), graphitization, and AMS measurement (following Zoppi et al. 2007). Given the unexpectedly wide range of AMS $\delta^{13}C$ values reported, it was felt necessary to repeat the AMS measurements at the Leibniz-Labor where possible. Enough mussel flesh and "alkali residue" remained for new combustions and AMS targets for KIA-45727, KIA-47068, and KIA-47071–3 to be prepared and dated in Kiel (following Nadeau et al. 1998).

Tables 1 and 2 give the AMS-measured $\delta^{13}C$ values and ^{14}C concentrations corrected for fractionation using either AMS or canonical $\delta^{13}C$ values. Fractionation-corrected ^{14}C concentrations ($F^{14}C$: Reimer et al. 2004) are converted to conventional ^{14}C ages (BP), following Stuiver and Polach (1977). For the modern samples, we also report *apparent* ^{14}C ages, obtained by recalculating the conventional ^{14}C ages using the estimated atmospheric ^{14}C concentration in summer 2011, 1.035 $F^{14}C$ (by extrapolation from Hua et al. 2013, Table S2a, Northern Hemisphere Zone 1) as the denominator in the age equation. The errors quoted do not account for uncertainty in this estimate, or in the length of time over which the samples formed, but other studies report a ~5‰ (0.005 F^{14}C) uncertainty in extrapolated atmospheric ^{14}C concentration, and a maximum seasonal variation of a similar order (Rakowski et al. 2013), so it is unlikely that these factors significantly affect the apparent ^{14}C ages. Any correction to account for a longer water residence time, or shell growth increment, would give marginally higher apparent ^{14}C ages, given the year-to-year decrease in Δ^{14}C in recent decades.

When the results of the replicated samples are compared, the ^{14}C ages are almost identical in two cases (KIA-47071 and KIA-47072), and broadly similar but statistically different in the other three cases (KIA-45727, KIA-47068, and KIA-47073). It is perhaps unrealistic to assume that different aliquots of bulk samples (that were not homogenized during pretreatment) should have consistent ^{14}C ages. The discrepancies are not simply caused by the use of canonical δ^{13}C values to correct some ^{14}C concentrations for natural fractionation. If only the AMS-measured δ^{13}C values were used, the ^{14}C ages for KIA-47073 would be consistent, but the discrepancy in the KIA-47068 ^{14}C ages would increase. Despite these reservations, our results provide the first direct evidence of the scale of ^{14}C depletion in the aquatic ecosystem at Lake Burtnieks.

DISCUSSION

The ages of emerged plant macrofossils appear to increase with depth in the Pantene 2 core (Figure 2), and we therefore assume that they reliably date the deposition of the *gyttja* layer, to the middle of the first half of the 5th millennium cal BC. If, as appears, the *Scirpus* seeds are not reworked or intrusive, we may also assume that the submerged-species macrofossils are approximately *in situ*, and of similar calendar ages to *Scirpus* seeds from corresponding levels. The differences in ^{14}C ages between submerged and emerged samples are thus likely to reflect ^{14}C depletion in lake water DIC.

Some reworking of plant macrofossils by bioturbation within the *gyttja* is perhaps inevitable, particularly between closely spaced bulk samples, and the ^{14}C ages of submerged samples can also be affected by photosynthesis at the surface, so it would be wrong to interpret any variation in ^{14}C-age offsets between dated levels as a change in reservoir age. What is important is that the ^{14}C-age offsets in all three submerged samples are of a similar order of magnitude, which suggests that carbon in submerged plant macrofossils was derived mainly from DIC, and that the ^{14}C-age offsets are therefore valid estimates of the reservoir age.

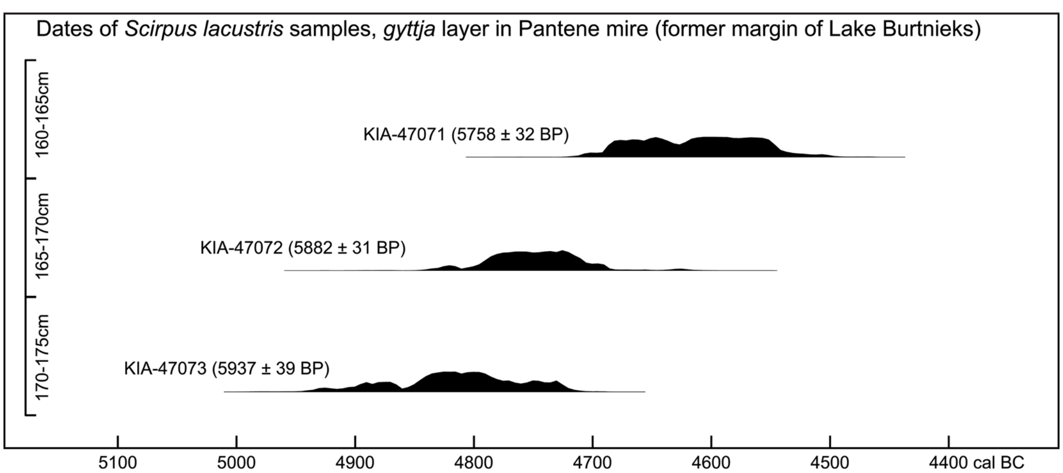

Figure 2 Calibrated dates of emerged-species macrofossils, plotted against depth in the Pantene paleoenvironmental sequence. The ^{14}C ages were calibrated using IntCal09 (Reimer et al. 2009) and OxCal v 4.2 (Bronk Ramsey 2009).

The results from modern samples suggest that DIC is the main or only source of carbon for shell-building by mollusks and photosynthesis by submerged plants. Given the ^{14}C results for mussel flesh, it appears that DOC and POC, which can be used by zooplankton and directly or indirectly by filter feeders such as mussels, are derived mainly from relatively recent organic sources (aquatic organisms and/or terrestrial vegetation), rather than the erosion of ancient peat beds (cf. Caraco et al. 2010). We have not measured ^{14}C in DOC and POC directly, partly because its interpretation is complicated by the ^{14}C bomb spike in recent vegetation, which could mask a contribution from ancient peat.

The apparent ^{14}C ages of ~800–900 BP in modern samples are comparable to ^{14}C-age offsets between the mid-Holocene emerged and submerged plant macrofossils. The ^{14}C "initial activity" of DIC in river water at Riņņukalns in 2011 was ~89.5% of that of contemporary atmospheric CO_2, whereas the plant macrofossil results imply that initial activity of DIC in Lake Burtnieks was ~88.8–90.7% of that of atmospheric CO_2 during the 5th millennium cal BC (Table 3). These estimates are remarkably close, suggesting that the mid-Holocene hydrological regime was similar to today's, notwithstanding the reduction in the lake's surface area over this period, which could have affected the rate of exchange between dissolved and atmospheric CO_2 and thus influenced the reservoir age (Geyh et al. 1998). Our estimated mid-Holocene reservoir age (~800–900 ^{14}C yr) is probably not applicable to the early Holocene, when a 1–2-m-thick layer of calcareous tufa was deposited along the western margin of Lake Burtnieks and in the Zvejnieki area (Eberhards 2006). Under these circumstances, much greater reservoir ages may be expected.

Now that we are confident that the midden layers are undisturbed and were deposited rapidly (Bērziņš et al., forthcoming), we can also estimate the relevant reservoir age by comparing ^{14}C ages of archaeological shells to those of fully terrestrial samples from the midden. Collagen is preserved in the fish bones, which will allow us to test how isotopically distinctive the main resident and migratory fish taxa are—including whether they have distinct ^{14}C ages (which, in combination with stable isotope values, may help to discriminate between diet and habitat). We have already identified one "visitor" to the site, a red-necked grebe (*Podiceps grisegena*), of which both ulnae and radii were found, together, in an undisturbed midden layer. This species should have a fully aquatic diet, yet its ^{14}C age is only about 300 ^{14}C yr older than that of the terrestrial species, which, together with an enriched $\delta^{13}C$ value, points to an estuarine-coastal diet, rather than residence at Lake Burtnieks (Bērziņš et al., forthcoming). The bird may have been caught accidentally as a byproduct of fishing (Zhilin and Karhu 2002), or it may have been hunted specifically for its wing bones, which were used to make beads (Mannermaa 2008), in which case it was not necessarily taken locally.

Table 3 Estimates of ^{14}C activity of lake water DIC, Lake Burtnieks, August 2011 and early 5th millennium cal BC.

	Modern samples (Table 1)	Paleoenvironmental samples (Table 2)		
	DIC	160–165 cm	165–170 cm	170–175 cm
Atmospheric[a] ^{14}C concentration ($F^{14}C$)	1.0350	0.4883	0.4813	0.4775
Aquatic[b] ^{14}C concentration ($F^{14}C$)	0.9263	0.4395	0.4271	0.4333
Initial activity of DIC (aquatic as % of atmospheric)	89.5	90.0	88.8	90.7

a. Estimated value for atmospheric CO_2 in mid-2011 (see text) and fractionation-corrected ^{14}C concentration in emerged species samples measured at Leibniz-Labor, Kiel.
b. Fractionation-corrected ^{14}C concentration in 2011 water sample and in submerged species samples measured at Leibniz-Labor, Kiel, and at a collaborating laboratory.

Our results imply that the Lake Burtnieks reservoir age in the mid-Holocene was large enough that even modest consumption of local aquatic species would produce measurable reservoir effects in human remains. We can therefore use ^{14}C-age offsets between human remains from undisturbed burials and associated grave goods from fully terrestrial species to inform the reconstruction of dietary and mobility patterns, ideally in combination with other proxies such as δ^{15}N and δ^{13}C. In a handful of cases, it is possible to test this approach using data published by Eriksson et al. (2003), Eriksson (2006), Zagorska (2006), Mannermaa (2008), and Larsson (2010) from burials in the Zvejnieki cemetery. Where multiple individuals and faunal samples from the same burial have been dated, the freshwater reservoir age proposed in this study may explain what would otherwise appear to be ^{14}C age anomalies.

The human in burial 208 (Ua-19815, 5345 ± 60 BP) is ~495 ± 85 ^{14}C yr older than a red deer grave good (4850 ± 60 BP, laboratory number not reported), and the human's stable isotopes (δ^{15}N 13.6‰, δ^{13}C –22.2‰) suggest freshwater fish consumption (enriched δ^{15}N, depleted δ^{13}C; Eriksson 2006). Burial 206 (Ua-3634, 5285 ± 50 BP), which stratigraphically cannot be earlier than burial 208, is ~435 ± 80 ^{14}C yr older than the 208 grave good; stable isotope data are unavailable. In the double burial 316–317, the humans' ^{14}C ages are statistically inconsistent with each other (LuS-8216, 5105 ± 50 BP; LuS-8217, 5285 ± 55 BP; $T = 5.9$, $T'(5\%) = 3.8$, $\nu = 1$; Ward and Wilson 1978), presumably due to dietary reservoir effects, as they should be identical in date. Both human ^{14}C ages are significantly greater than that of a dagger, made from a red deer ulna, which is regarded as a grave good (LuS-7852, 4865 ± 60 BP). Again, stable isotope measurements for these individuals are not reported, but ^{14}C-age offsets of ~240 ± 80 and ~420 ± 80 yr suggest that they obtained roughly a quarter to a half of their dietary protein from aquatic foods, assuming that these were as ^{14}C depleted as the local DIC.

Human ^{14}C ages are not significantly different to those of herbivore bone/antler grave goods in two cases, burial 137 (human: Ua-19811, 4280 ± 60 BP; "goat" bone chisel, 4400 ± 85 BP, laboratory number not reported; $T = 1.3$, $T'(5\%) = 3.8$, $\nu = 1$; Ward and Wilson 1978) and the multiple burial 220–225 (human 221: Ua-19813, 5180 ± 65 BP; human 225: OxA-5986, 5110 ± 45 BP; elk, 5290 ± 105 BP, laboratory number and skeletal element not reported; $T = 2.8$, $T'(5\%) = 6.0$, $\nu = 2$; Ward and Wilson 1978). The available isotope data (human 137, δ^{15}N 9.7‰, δ^{13}C –21.6‰; human 221, δ^{15}N 12.7‰, δ^{13}C –21.3‰) suggest diets at or towards the terrestrial end of the range at Zvejnieki (Eriksson 2006). We would therefore not expect large ^{14}C age offsets in these cases.

Three humans from a mass grave, burials 178–182, gave ^{14}C ages that are statistically inconsistent with a single date (burial 178: Ua-19806, 6185 ± 80 BP; burial 179: Ua-19807, 5895 ± 70 BP; burial 182: OxA-5970, 6005 ± 75 BP; $T = 7.5$, $T'(5\%) = 6.0$, $\nu = 2$; Ward and Wilson 1978). Stable isotopes were measured in burials 178 and 179. It was argued that the individual with the lower ^{14}C age had a more aquatic diet (burial 179, δ^{15}N 12.0‰, δ^{13}C –23.8‰; burial 178, δ^{15}N 10.8‰, δ^{13}C –22.8‰; Eriksson et al. 2003:61), but a second stable isotope sample from burial 179 (δ^{15}N 10.5‰, δ^{13}C –22.6‰) gave results indistinguishable from those attributed to burial 178 (Eriksson 2006). Even if burial 179 ate more fish than burial 178, their ^{14}C-age differences are explicable by dietary reservoir effects—with some variability in the ^{14}C age of freshwater fish consumed, perhaps due to human mobility.

Two other cases may be relevant to this discussion. In burial 165, the human ^{14}C age (Ua-19812, 5480 ± 100 BP) is 230 ± 110 yr greater than that of a woodland bird, the jay (*Garrulus glandarius*, Hela-1216, 5250 ± 55 BP), whose diet should be terrestrial in origin. Uniquely at Zvejnieki, human stable isotope values (δ^{15}N 12.0‰, δ^{13}C –18.8‰) suggest a partly marine diet, which would give rise to a smaller reservoir effect than local freshwater fish. In burial 164, a loon (*Gavia* sp.) bone was dated 540 ± 110 ^{14}C yr older than the human bone, whose stable isotopes (δ^{15}N 11.7‰,

$\delta^{13}C$ –22.1‰) suggest only modest freshwater fish consumption (Hela-1215, 5770 ± 55 BP; Ua-15544, 5230 ± 95 BP). As the loon feeds almost exclusively on aquatic organisms, we can reconcile these results with a single date of burial, if the local freshwater reservoir age is of a similar order to that indicated by the Riņņukalns and Pantene data.

In the remaining instances in which more than one sample from the same grave was dated, it is likely that the samples are not the same calendar age, due to the magnitude of ^{14}C age discrepancies. In several cases, faunal samples were dated thousands of ^{14}C years older than the "associated" humans, and these samples must be residual (older than the burials concerned). On the other hand, an owl bone (*Strigiformes* sp., presumably with a terrestrial diet) from burial 256 (Hela-1214, 4480 ± 45 BP) appears to be more recent than the human bone (Hela-1213, 5320 ± 45 BP), unless this individual's diet consisted almost entirely of local freshwater species; no isotope data are available, but such a diet seems implausible.

At Riņņukalns, the ^{14}C-dated human remains were disassociated from their burial context, although future excavation may uncover further undisturbed prehistoric burials. The disarticulated prehistoric human bone found in the midden during the 2011 excavation has a ^{14}C-age offset of ~370 ± 30 yr, compared to the weighted mean of four *in situ* terrestrial samples (Bērziņš et al., forthcoming), which we regard as a *maximum* reservoir effect, as the human bone was redeposited in layer 15 when an earlier burial was disturbed. Its stable isotope values (see above) suggest a diet based heavily on freshwater protein sources, however, which implies that this individual may have also consumed nonlocal aquatic foods, or that important fish species were less ^{14}C depleted than the local DIC. Our understanding of prehistoric human diet and mobility, therefore, depends on understanding the isotopic signatures of all the significant dietary species in the midden deposits. Given tight chronological associations between samples, and spatial variability in ^{14}C depletion, ^{14}C can serve as a tracer of dietary or residential patterns. Terrestrial, marine, and freshwater resources have reasonably distinct stable isotope signatures; ^{14}C may discriminate between different species and freshwater systems.

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