**The adoption of pottery by North-East European hunter-gatherers: evidence from lipid residue analysis**

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## Abstract

Pottery was adopted by hunter-gatherers in the Eastern Baltic at the end of the 6th millennium cal BC. To examine the motivations for this cultural and technological shift, here we report the organic residue analysis of ceramic vessels from the earliest pottery horizon (Narva) in this region. A combined approach using GC-MS, GC-C-IRMS and bulk IRMS of residues absorbed into the ceramic and charred surface deposits was employed. The results show that despite variable preservation, Narva ceramic vessels were preferentially used for processing aquatic products. We argue that pottery was part of a new Late Mesolithic subsistence strategy which included more intensive exploitation of aquatic foods and may have had important implications, such as increased sedentism and population growth.

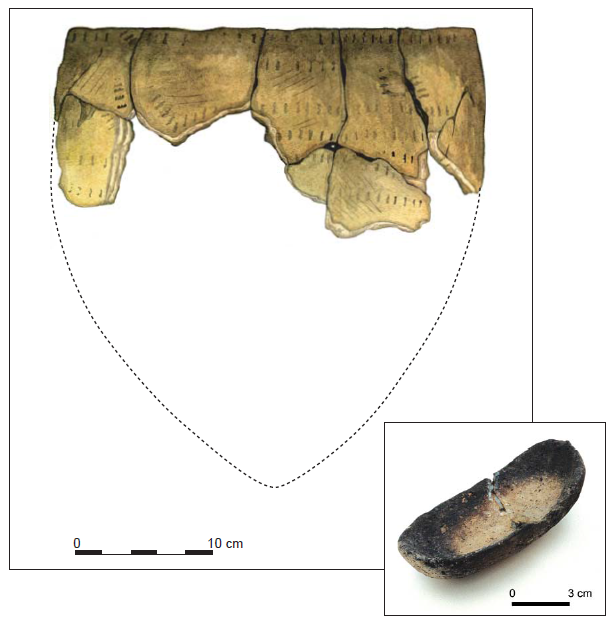
**Keywords:** lipid residue analysis, early pottery use, aquatic resources, Mesolithic, Neolithic, Eastern Baltic

## Introduction

The arrival of pottery marks a clear archaeological horizon in the Northern Eurasian prehistoric sequence, and is often synonymous with the period known as the Neolithic, despite predating agriculture by several thousand years. In the Eastern Baltic this transition occurred during the late 6th millennium cal BC, and may have been part of an east-west expansion of pottery technology from the Eurasian steppe [(Dolukhanov et al., 2005; Piezonka, 2015)](https://paperpile.com/c/sHVo0a/OCJV) and even further east from the Palaeolithic ceramic cultures of Eastern Russia and Japan [(Gibbs, 2015; Gibbs and Jordan, 2013; Silva et al., 2014)](https://paperpile.com/c/sHVo0a/90VX+VROe+E5MT). It has been proposed that pottery containers were part of a pre-farming package of technological innovations that led to more intensive food procurement, increased sedentism, higher population densities and the development of new exchange networks (Jordan and Zvelebil, 2009; Nordqvist and Kriiska, 2015). In this sense, pottery may have been as important as the agriculture in guiding Europe's subsequent cultural trajectory. The appearance of pottery certainly correlates with the flourishing of a broad range of late foragers across the Baltic in the 5th millennium cal BC, which also corresponds to the Holocene Thermal Maximum (e.g. Seppä et al., 2009). However, the motivations for the introduction of pottery at this juncture in Baltic prehistory remain unclear. Indeed, in the Eastern Baltic, there seems to be little evidence for dramatic changes in the subsistence economies or settlement patterns following the first appearance of ceramic vessels (Kriiska et al., forthcoming) and an alternative hypothesis is that pottery made a rather ‘silent’ impact despite their visibility in the archaeological record. Instead of transforming prehistoric societies and economies, pottery may have merely represented a small step in container evolution fulfilling niches already occupied by perishable containers.

To clarify their role and potential impact on the local economy, here we provide the first evidence of the use of pottery belonging to the earliest ceramic phases of the Eastern Baltic using lipid residue analysis. This approach involves the chemical and isotopic characterisation of lipids that become deposited within ceramic or charred surface deposits during their use (Evershed et al., 2001; Evershed, 2008; Craig et al., 2004; 2012). Lipid residue analysis has been applied to study pottery use by East Asian foragers [(Craig et al., 2013; Lucquin et al., 2016)](https://paperpile.com/c/sHVo0a/n4Ik+6X7D) and by early farmers in Europe and the Near East [(Copley et al., 2002; Cramp et al., 2014; Evershed et al., 2008b)](https://paperpile.com/c/sHVo0a/kqRg+dKng+26hd). However, far less attention has been given to the uptake and use of pottery by European foragers, although there has been some work on the western Baltic ceramic hunter-gatherers (Papmehl-Dufay 2006; Isaksson, 2009; Craig et al., 2011).

Our study focuses on the Narva culture of Estonia dating from the late 6th to the 5th millennium cal BC (Piezonka, 2012; 2015; Kriiska et al., forthcoming), perhaps the best known example of pottery using foragers in the Eastern Baltic. Narva-type ceramics include several different forms, from pointed-base vessels and shallow oblong bowls and represent the earliest pottery complex of this region. They are characterised by striated or smoothed surfaces, but sometimes also decorated with pits, notches, grooves and comb impressions (Fig. 1). This pottery type is distributed across a range of hunter-gatherer societies throughout the Baltic countries, North-West Russia and Belorussia. Although, the technological aspects of Narva vessels have been well studied (e.g. Kriiska, 1996; Mikšaitė, 2005), direct chemical evidence of their use is currently missing.



**Fig. 1. Examples of Narva-type vessels from Estonia.** Reconstruction of the Narva-type pot and shallow oblong bowl from Kääpa. Drawing by Diana Selli and photo by Kriiska et al., 1999.

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## 2. Material and methods

### 2.1. Narva pottery and sites analysed

In Estonia, there are around 30 known Narva settlements, including the type site Narva Joaorg, and four Narva burial sites. Settlements cover coastal, island, lagoon and inland areas, and include both short-term seasonal camps and long-term habitation sites. Here we targeted a wide selection of sites from different environmental and habitational contexts. The multi-site comparative approach was chosen to determine whether the earliest pottery in this region had a common use or whether use varied by site type and environmental conditions. The dates from Narva stage sites in Estonia range from 5200–3900 cal BC with directly dated Narva sherds from 4850–4710 cal BC and 4590–4440 cal BC (Kriiska et al., forthcoming). The latter were also included in current analysis. In total 100 samples from 65 sherds and 12 different Narva sites all over Estonia (Fig. 2; Table 1) were analysed.

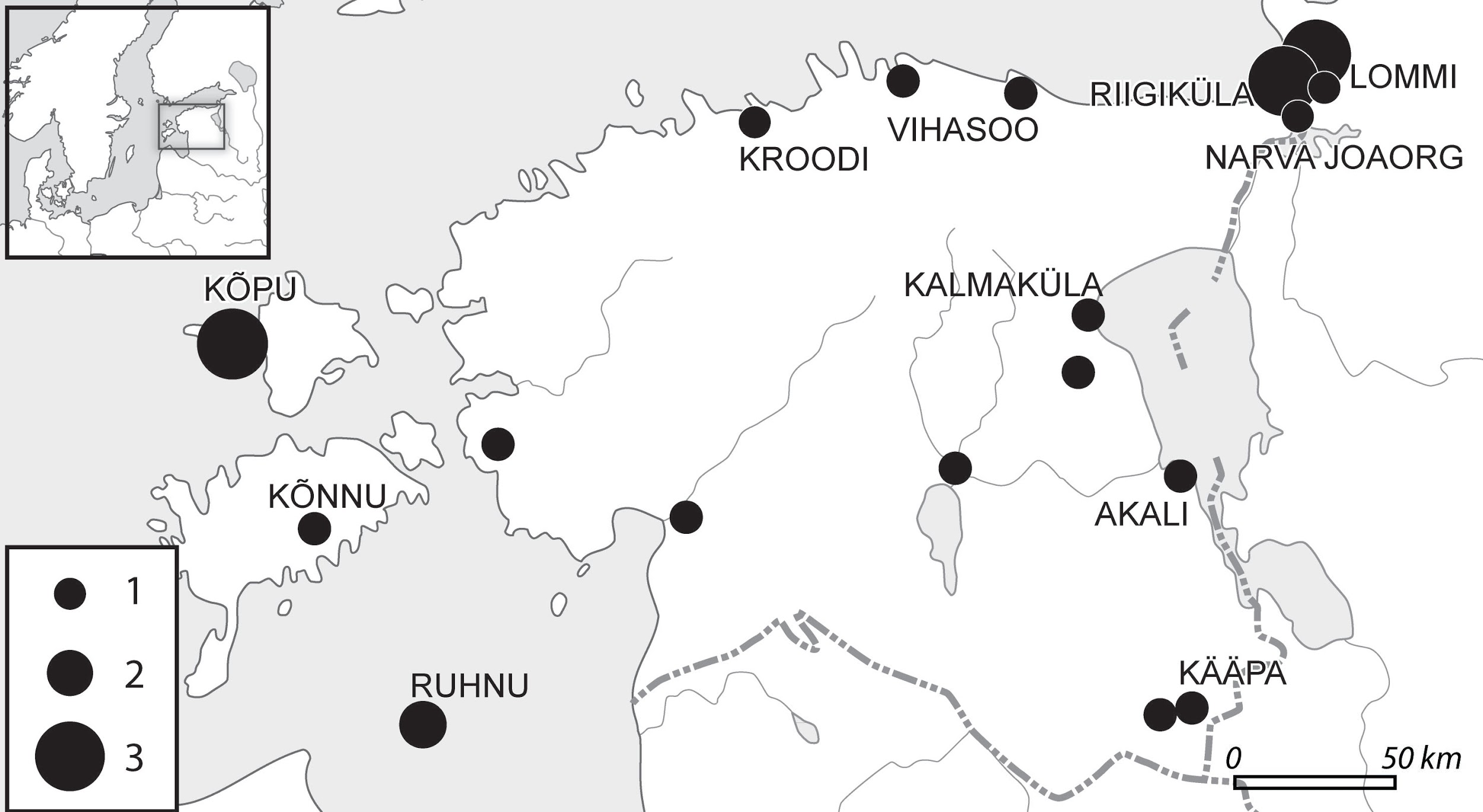
**Table 1. Samples and results of residue analysis.**

| **Site** | **Location** | **No. vessels** | **No. samples** | **Sample types** | **Lipid preservation (ug g-1) range / median** | **No. vessels with lipids preserved\*** | **No. vessels with aquatic biomarkers\*\*: full (partial)** | **GC-C-IRMS samples** | **Bulk IRMS samples** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Akali | Inland | 6 | 9 | Fi 3, I 6 | 20-1230 / 205 | 6 | 2 | 5 | 3 |
| Kääpa | Inland | 21 | 41 | Fe 6, Fi 16, I 19 | 8-2513 / 357 | 21 | 14 (3) | 29 | 19 |
| Kalmaküla | Inland | 2 | 2 | I 2 | 3-10 / NA | 1 |  |  |  |
| Kõnnu | Coastal | 5 | 9 | Fe 1, Fi 3, I 5 | 9-80 / 40 | 5 | 1 (1) | 4 | 4 |
| Kõpu I | Coastal | 1 | 1 | I 1 | 38 / NA | 1 |  |  |  |
| Kroodi | Lagoon (?) | 1 | 2 | Fi 1, I 1 | 67-75 / NA | 1 | (1) | 1 | 1 |
| Lommi | Lagoon | 5 | 5 | I 5 | 17-104 / 25 | 5 |  | 3 |  |
| Narva Joaorg | Estuary | 14 | 20 | E 1, Fi 5, I 14 | 2-171 / 48 | 13 | 2 | 7 | 3 |
| Riigiküla IV | Lagoon | 2 | 2 | I 2 | 35-86 / NA | 2 |  |  |  |
| Riigiküla VI | Lagoon | 2 | 3 | E 1, I 2 | 52-73 / NA | 2 |  |  |  |
| Ruhnu II | Coastal | 1 | 1 | I 1 | 72 / NA | 1 | 1 | 1 |  |
| Vihasoo III | Estuary | 5 | 5 | I 5 | 31-84 / 44 | 5 |  | 3 |  |
| **TOTAL** |  | **65** | **100** |  |  | **63** | **20 (5)** | **53** | **30** |

I/i – Internal surface; E/e – External surface; F – Food crust.

\* lipid preservation greater than 0.1 µg mg-1 of food crust or 5µg g-1 of ceramic powder.

\*\* full aquatic biomarkers - alkylphenyl fatty acids in C18-22 and isoprenoid fatty acids (phytanic, pristanic, 4,8,12-trimethyltridecanoic acid) or alkylphenyl fatty acids in C20-22; partial aquatic biomarkers - alkylphenyl fatty acids in C18 and isoprenoid fatty acids.



**Fig. 2. The sites of Narva stage in Estonia and Ingermanland (Russian Federation) with the sites analysed for lipid residues marked with names.** 1 – one settlement site, 2 – from two to five settlement sites, 3 – six or more settlement sites. Map by Aivar Kriiska, technical realization Kristel Roog and Ester Oras (from Kriiska et al., forthcoming)

### 2.2. Methods

Where available, both carbonised deposits or food crusts, visible on the pottery surface (ca. 20 mg of sample for GC-MS and 1 mg for bulk IRMS) and ceramic matrices (ca. 1 g) were mechanically removed. Lipids were extracted using a one-step acid/methanol extraction technique following previously established extraction protocols (Craig et al., 2013; Colonese et al., 2015; Heron et al., 2015; Papakosta et al., 2015). Briefly, acid catalysed lipid extraction and methylation with MeOH (70º C, 4 h) was conducted after which lipids were extracted with *n*-hexane (3 × 2 ml). The samples were dried up under the stream of nitrogen at 37.5º C, dissolved in 100µl of *n*-hexane with the addition of 10 µg of internal standard of C36:0 (*n*-hexatriacontane) and analysed directly with GC-FID, GC-MS, and GC-C-IRMS.

General screening and quantification of the lipid extract was carried out by GC-FID (gas chromatography - flame ionization detector) using an Agilent 7890A gas chromatograph (Agilent Technologies, Cheadle, Cheshire, UK). The injector was splitless and maintained at 300 °C. One µl of sample dissolved in hexane was injected into the GC. The column used was a 100% Dimethylpolysiloxane DB-1 (15 m x 320 µm x 0.1 µm; J&W Scientiﬁc, Folsom, CA, USA). The carrier gas was hydrogen with a constant flow rate of 2 ml min-1. The temperature program was set at 100 °C for 2 minutes, rose by 20 °C min-1 until 325 °C. This temperature was maintained for 3 minutes. Total run time was 16.25 minutes. The lower boundaries of interpretable archaeological lipid extract were 0.1 µg mg-1 of food crust corresponding roughly to 2µg of extracted lipids (Craig et al., 2013) or 5µg g-1 of ceramic powder corresponding roughly to 5µg of extracted lipids (Evershed, 2008).

GC-MS (gas chromatography-mass spectrometry) analysis was performed with Agilent 7690A Series gas chromatography and Agilent 5975C Inert XL mass-selective detector with a quadrupole mass analyser with Triple-Axis Detector (Agilent Technologies, Cheadle, Cheshire, UK) were used. The splitless injector and interface were maintained at 300°C and 280 °C respectively. One µl of sample dissolved in hexane was injected. Helium was the carrier gas at constant inlet pressure. The GC column was inserted directly into the ion source of the mass spectrometer. The ionisation energy was 70 eV and spectra were obtained by scanning between m/z 50 and 800. All samples were analysed using a DB5-ms (5%-phenyl)-methylpolysiloxane column (30 m × 0.32 mm × 0.25 µm; J&W Scientific, Folsom, CA, USA) with the temperature program of 2 min at 50°C, 10°C min–1 to 325°C and 15 min at 325°C. The identification of compounds was conducted with the Agilent Chemstation software according to their mass spectrum, their retention time and with the help of NIST 2008 library of mass spectra.

GC-C-IRMS (gas chromatography-combustion-isotope ratio mass spectrometry) analysis of the samples with sufficient lipid preservation was conducted in order to estimate the 13C/ 12C ratio in two most abundant C16:0 and C18:0 fatty acids. This analysis provides further information for distinguishing different substances.

The samples were analysed using an Agilent 7890B GC (Agilent Technologies, Santa Clara, CA, USA) instrument coupled to an Agilent 5975C MSD and an Isoprime 100 IRMS (Isoprime, Cheadle, UK) with an Isoprime GC5 interface (Isoprime, Cheadle, UK). All samples were diluted with hexane and subsequently 1 µl of each sample was injected into a DB-5MS (30 m × 0.25 mm, 0.25 µm) fused-silica column. The temperature was set for 0.5 min at 50°C, and raised by 10°C min-1 until 300°C was reached, and held for 10 min. The carrier gas was ultra-high purity grade helium with a flow rate of 3 ml min-1. The gases eluting from the chromatographic column were split into two streams. One of these was directed into an Agilent 5975C inert mass spectrometer detector (MSD), for sample identification and quantification, while the other was directed through the GC5 furnace held at 850°C to oxidise all carbon species to CO2. A clear resolution and baseline separation of the analysed peaks was achieved in both systems

Eluted products were ionized in the mass spectrometer by electron impact. Ion intensities of *m/z* 44, 45, and 46 were monitored in order to automatically compute the 13C/12C ratio of each peak in the extracts. Computations were made with IonVantage and IonOS Softwares (Isoprime, Cheadle, UK) and were based on comparisons with a standard reference gas (CO2) of known isotopic composition that was repeatedly measured. The results from the analysis are reported in parts per mille (‰) relative to an international standard (V-PDB).

The accuracy and precision of the instrument was determined on *n*-alkanoic acid ester standards of known isotopic composition (Indiana standard F8-3). The mean ± S.D. values of these were -29.82 ± 0.16‰ and -23.28 ± 0.19‰ for the methyl ester of C16:0 (reported mean value vs. VPDB -29.90 ± 0.03‰) and C18:0 (reported mean value vs. VPDB -23.24 ± 0.01‰) respectively. Each sample was measured in replicate (mean of S.D. 0.11‰ for C16:0 and 0.10‰ for C18:0). Values were also corrected subsequent to analysis to account for the methylation of the carboxyl group that occurs during acid extraction. Corrections were based on comparisons with a standard mixture of C16:0 and C18:0 fatty acids of known isotopic composition processed in each batch under identical conditions.

Bulk IRMS (isotope ratio mass spectrometry) analysis of food crusts determining δ13C and δ15N relative to VPDR and AIR internal standards was conducted at the facilities at the University of York BioArCh laboratory and Department of Geology at the University of Tartu. Ca. 1 mg food crust sample was weighed into tin capsules. At the University of Tartu Institute of Geology IRMS facility the samples were analysed with Thermo Scientific Delta V Plus + Thermo Finnigan Flash HT Plus using IAEA-N2 standards (the mean ± S.D. values within run 20.299 ± 0.1482), IAEA-CH3 (-24.611 ± 0.0244‰), IAEA-CH6 (-10.52 ± 0.0335‰). At the York BioArCh Light Stable Isotope facility the instrument used was Sercon continuous flow 20-22 Isotope Ratio Mass Spectrometer with universal Faraday triple collectors (C, N, S, O) with the international standards of IAEA-N2 (20.30 ± 0.2‰) and IAEA-600 (caffeine; -27.77 ± 0.04‰), complemented with the lab standards of fish-gel and cane sugar.

## 3. Results

## 3.1. GC-MS analysis

In total 93 samples from 65 sherds were analysed by GC-MS, comprising 65 ceramic samples and 28 food crusts. An interpretable lipid residue (i.e. >5µg g-1 sherd or >0.1 µg mg-1 food crust) was present in 87 samples derived from 63 sherds/vessels. Lipid preservation varied considerably across the sites investigated with submerged inland sites (Kääpa and Akali) yielding the highest amounts and coastal sites the lowest (Table 1). Besides the environmental conditions lipid preservation may also depend on different uses of the vessels, as well as the nature of the clay matrix affecting absorption of lipids.

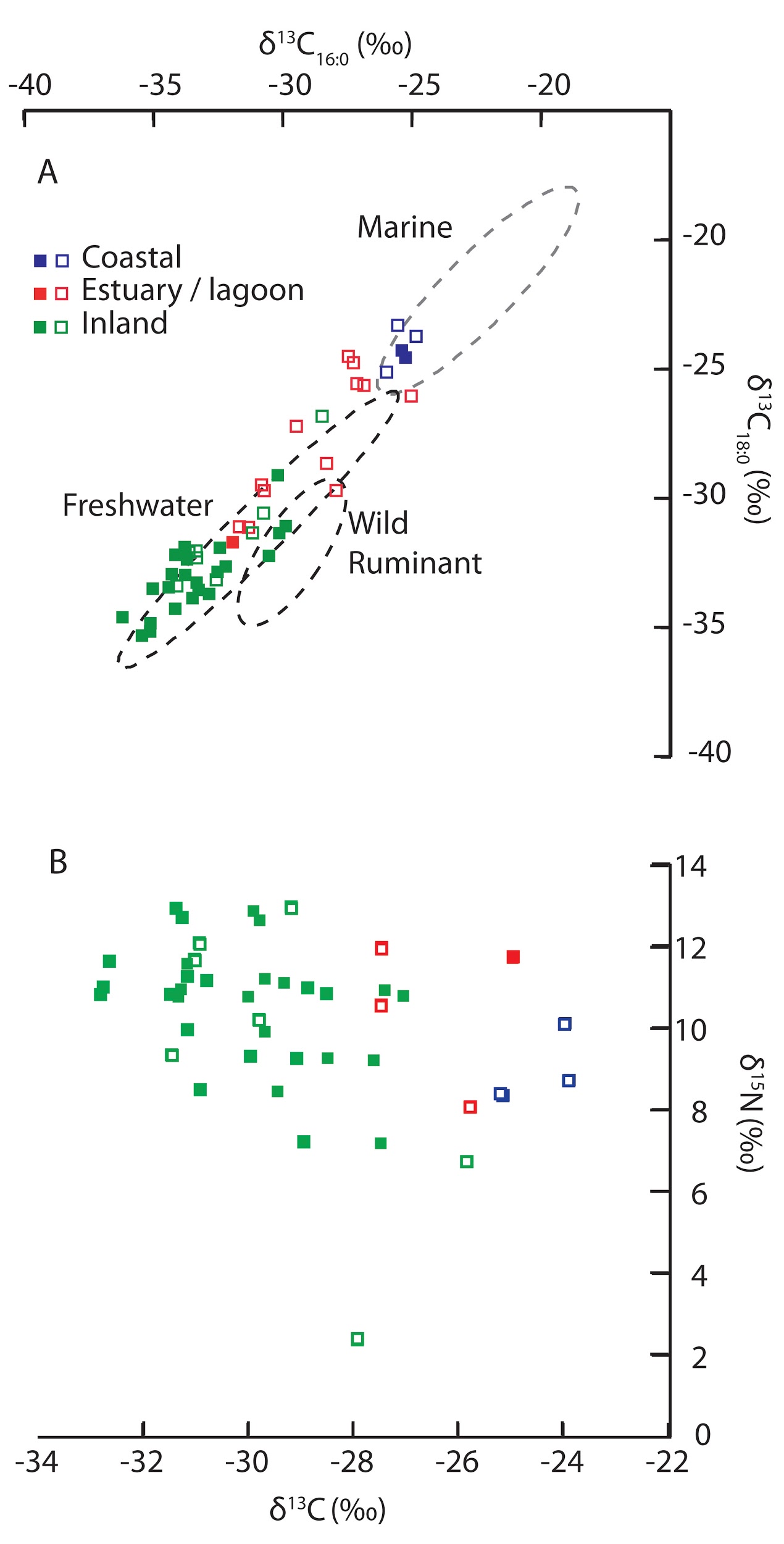
Twenty seven of samples contained *ω*-(*o*-alkylphenyl) alkanoic acids (APAAs), with carbon atoms ranging from C18 to C22 and isoprenoid fatty acids (phytanic, pristanic, and 4,8,12-trimethyltridecanoic (TMTD). The former are formed by prolonged heating of polyunsaturated fatty acids found in aquatic organisms (Hansel et al., 2004; Craig et al., 2007) and therefore must be derived from primary use of the vessel. Together the presence of these compounds meet the molecular criteria for aquatic organisms [(Evershed et al., 2008a)](https://paperpile.com/c/sHVo0a/nUsp) and are frequently found in other prehistoric forager pottery vessels from East Asia [(Craig et al., 2013; Lucquin et al., 2016)](https://paperpile.com/c/sHVo0a/n4Ik+6X7D), North America [(Taché and Craig, 2015)](https://paperpile.com/c/sHVo0a/OQ4h) and the Baltic [(Papmehl-Dufay, 2008; Isaksson, 2009; Craig et al., 2011; Cramp et al., 2014)](https://paperpile.com/c/sHVo0a/VH6X). Four samples included only C20 and/or C22 APAA without isoprenoid fatty acids, which are also considered as aquatic biomarkers. A further seven samples contained partial sets of aquatic biomarkers, i.e. C18 APAA and isoprenoid fatty acids. These are most likely derived from aquatic organisms but it is important to note that C18 APAAs may also be formed from by heating other mono- and polyunsaturated fatty acids found in plant oils and terrestrial animal fats.

Cholesterol and various derivatives (e.g. cholestadiene, cholesterol methyl ether, cholestanol etc.) were identified in over one third of the samples hinting at animal-related substances. However, these can be both aquatic and terrestrial animals. In the vast majority of samples (83 in total), several diterpenes derived from *Pinaceae* resins (Pollard and Heron, 2008, 242; Modugno and Ribechini, 2009) were observed (Appendix A. Supplementary data). These compounds were at low abundance rather than the main constituent of the organic residue and include dehydroabietic acid, 7-oxodehydroabietic acid and retene. As retene will appear only with a protracted heating, contamination from surrounding soil can be excluded but these compounds may have be formed during the firing of the pot or potentially from woodsmoke during use (Simoneit et al., 2000). Another explanation would be that resins have been used to waterproof the pots.

### 3.2. GC-C-IRMS analysis

The determination of the δ13Cvalues of the C16:0 and C18:0 fatty acids provides further information on the origin of organic residues associated with ceramic vessels (Evershed 2008; Craig et al. 2012). It is noticeable that majority of sherds analysed (29 out of 31) from inland sites, have fatty acid δ13C values below -30‰ (Fig. 3A). These are consistent with reported ranges for fatty acids from freshwater fish [(Cramp and Evershed, 2014)](https://paperpile.com/c/sHVo0a/H9mn), although plant oils and fats from non-ruminant herbivores, such at beaver (*Castor fiber*) may have similar values [(Taché and Craig, 2015)](https://paperpile.com/c/sHVo0a/OQ4h). However, when the molecular data is also considered, these terrestrial products are less likely as many of the samples contained full sets of aquatic biomarkers (Fig. 3A) and nearly all have isoprenoid fatty acids that are not typically found in plants and terrestrial non-ruminant tissues. Conversely, vessels from coastal sites have more enriched fatty acid δ13C values, consistent with marine foods, whilst those from brackish lagoonal sites have intermediate values, falling between the expected ranges for marine and freshwater fish. Lipids were much poorer preserved at these coastal and brackish lagoonal sites compared to inland, explaining the lack of aquatic biomarkers in the majority of samples analysed. Overall, the observed correspondence between site location and fatty acid δ13C values implies that locally caught fish was the principal commodity selected for processing in pottery from this region.

Based on GC-C-IRMS data, only four samples, of which two are from the same sherd, fall within the range of ruminant fats, although these also match the reference range for freshwater fish (Fig 3A). These data contrast with the high abundance of ruminants, such as elk (*Alces alces*), observed in the faunal assemblages, and therefore we can conclude that tissues from this animal were not routinely processed in Narva pottery. Even where the GC-C-IRMS data were consistent with ruminant fats, these samples also contained ω-(o-alkylphenyl) alkanoic acids in the range of C16-20.Therefore, if present at all, it is likely that terrestrial ruminant fats were mixed or sequentially processed with fish oils. Another explanation is that these GC-C-IRMS data are derived from the mixing of fatty acids from freshwater, terrestrial and marine lipids, although this would seem less likely for the samples from inland sites.



**Fig. 3. Bulk and single compound stable isotope analysis of Estonian Narva pottery from different environmental contexts. A –** Plot of δ13C values of C16:0 and C18:0 *n-*alkanoic acids extracted Narva vessels from inland, estuary/lagoon and coastal sites. The data are compared to ranges for authentic reference lipids from modern tissues and archaeological bone (66.7% confidence) as previously reported [(Lucquin et al., 2016)](https://paperpile.com/c/sHVo0a/6X7D). **B** **–** Plot of bulk carbon (δ13C) against nitrogen (δ15N) isotope values for charred surface deposits from Narva vessels. Samples meeting the molecular criteria for aquatic products are shown by filled symbols.

### 3.3. Bulk IRMS analysis

Overall the bulk IRMS results agree with the GC-C-IRMS data indicating that aquatic substances were the most dominant product processed in Narva pottery. For example, food crusts on pots from inland sites are generally depleted in 13C compared to estuarine and coastal sites. The majority of vessels have δ15N values above 8‰ (Fig. 3B) and atomic C:N ratios less than 15 (Appendix A. Supplementary data), broadly consistent with the processing of medium and high trophic level marine or freshwater products, as demonstrated experimentally [(Craig et al., 2011)](https://paperpile.com/c/sHVo0a/VH6X). The values are similar to previous analysis of forager pots from different archaeological sites with molecular evidence for the exploitation of fish and marine mammals [(Craig et al., 2011; Lucquin et al., 2016; Taché and Craig, 2015)](https://paperpile.com/c/sHVo0a/OQ4h+VH6X+6X7D) Only one sample from the site of Akali had a much lower δ15N value (2.4‰) and higher C:N ratio (~19) and therefore more typical of terrestrial plants. Overall, while most bulk isotope values are consistent with aquatic products, care needs to be taken in interpreting these measurements. Isotope values of bulk organic matter are susceptible to diagenetic change and only crudely reflect the original organic source [(Heron and Craig, 2015)](https://paperpile.com/c/sHVo0a/ti6j).

*3.4. Difference in between vessel typologies*

At Kääpa it was possible to compare the organic residue data between vessel types i.e. pointed-base vessels (pbv) and shallow oblong bowls (ob). The latter are sometimes interpreted to be oil lamps (Bērziņš 2008). The proportions of sherds with aquatic biomarkers were similar for both typologies (Appendix A. Supplementary data). Both types also had similar distributions of fatty acid carbon isotope values strongly suggesting in most cases that these were used for processing freshwater fish, as outlined above. However, the distribution of δ13C values of the food crusts on the oblong bowls (n=9) were significantly different to the pointed-base vessels (n=10; Kruskal-Wallis Test, H=4.86, p=0.027) with lower δ13C values obtained on bowls (e.g. medianob = -31.15‰; medianpbv = -29.49‰). No difference was observed in δ15N values. Also the food crusts on the oblong bowls had higher atomic C:N ratios (medianob = 12.48 ‰; medianpbv = 8.41‰) and the distributions of these values were significantly different between vessel types (Kruskal-Wallis Test, H = 5.61, p=0.018). An increase in the carbon to nitrogen ratio and a decrease in δ13C values is consistent with the hypothesis that substances relatively richer in lipids were processed in the oblong bowls compared to the pointed-base vessels, supporting the idea that they were used as oil lamps for illumination (Heron et al., 2013). Similar differences in bulk isotopic values between vessel types have been detected in the Lithuanian Neolithic sites of Nida and Šventoji (Heron et al., 2015).

## 4. Discussion

### 4.1. Comparison between pottery use and other evidence for subsistence strategies

When the data from absorbed residues and food crusts are combined, 20 vessels could be unequivocally associated with the processing aquatic organisms, i.e. either marine, freshwater or brackish species (Table 1). This is the minimum number as the diagnostic biomarkers are unlikely to be formed in all cases, and the preservation was highly variable between sites. For example if we consider vessels from Kääpa alone, the site with the best preservation, 14 out of 21 vessels contained the full set of aquatic biomarkers. The number rises further to 17 for Kääpa and 25 for all sites, if partial sets of biomarkers are considered, i.e. when isoprenoid and C18 APAA were detected in the same extract. An even stronger and more compelling case is made, when the stable carbon isotopic characteristic of charred surface deposits and fatty acids extracted from the vessels are considered, as these in almost all cases are strongly influenced by the local aquatic isotope ecology (Fig. 3). If terrestrial plants or animals were routinely processed in Narva pottery, we would not expect to see such isotopic variation by site location; studies of animal bone collagen have shown that the isotope composition of wild terrestrial herbivores does not change between coastal and inland locations (Piličiauskas et al., in prep).

Overall, therefore, there was a clear inclination towards the use and exploitation of aquatic substances during the first pottery producing people of the Eastern Baltic regardless of the environments they inhabited and habitation contexts, the latter covering inland long-term settlements and seasonal hunting sites. Although it is difficult to know, the variety of vessels types and the nature of the residues are consistent with direct consumption of fish in stews, the rendering and storage of oils, and their non-culinary uses, including fuel for illumination. Feasibly, such products could also have been modified to be used as moisturisers, sealants, adhesives, glues and lubricants.

Considering the general substance economy and zooarchaeological record of the sites, these findings are unexpected. At Narva Joaorg and Kääpa, where large faunal assemblages are available, (European) elk, wild boar, brown bear, beaver are all well represented together with freshwater fish (Paaver, 1965; Lõugas, 1996a, b; Paaver and Lõugas, 2003). Whilst difficult to quantify or directly compare due to biases in taphonomy and recovery, terrestrial animal bone make up over 35% of the faunal assemblage at Kääpa and over 90% at Narva Joaorg by NISP(Paaver, 1965; Lõugas, 1996a, b; Paaver and Lõugas, 2003).

The available human stable isotope data for the Narva period is also consistent with a diet derived from a mixture of aquatic and terrestrial sources, including plants (Tõrv, 2016). For example, at Narva Joaorg plant foods are suggested to make the highest contribution to protein intake by weight, followed by freshwater fish and then terrestrial animals. However, stable isotope evidence for fish consumption is clearly evident, supporting the lipid residue data (Fig 4). For example, humans buried at the coastal site of Kõnnu (see Fig. 2) have bone collagen clearly enriched in 13C compared to those at inland and estuarine sites, attributed to marine fish consumption at the former compared to freshwater at the latter (Tõrv, 2016). At the multi-period site of Zvejnieki on Lake Burtnieks in Latvia**,** the isotope analysis shows an increase in terrestrial animal and plants during this Narva phase compared to previous periods [(Eriksson et al., 2003; Meadows et al., 2016)](https://paperpile.com/c/sHVo0a/HqiP), although freshwater fish continued to be important. Interestingly however, the observed broadening of diets reflected in the stable isotope data may have predated the introduction of pottery by a few hundred years [(Meadows et al., 2016)](https://paperpile.com/c/sHVo0a/HqiP).



**Fig. 4. The carbon and nitrogen stable isotope data from human bone collagen from four Narva period sites in Estonia** (adapted from Tõrv, 2016; Tõrv and Eriksson, forthcoming). Green **–** inland riverine sites, red **–** river estuarine sites, blue **–** coastal sites.

### 4.2. Evidence for an ‘aquatic Neolithic’ in NE Europe?

The use of early pottery in Estonia is similar to both Finnish and Lithuanian Comb Wares (Leskinen, 2003; Pesonen and Leskinen, 2009; Cramp et al., 2014; Heron et al., 2015), which date to the 4th millennium cal BC, and late 5th millennium cal BC Scandinavian Ertebølle vessels (Craig et al., 2007; 2011; Heron et al., 2013; Philippsen and Meadows, 2014). In these later Baltic contexts, there is also evidence for specialization in the use of pottery for storing and processing aquatic products, despite the fact that ruminant and other animal fats were widely available. This general picture allows us to strengthen the hypothesis that forager pottery was widely adopted or independently invented by Holocene hunter-gatherers as part of a specialised toolkit allowing more efficient exploitation of aquatic resources (Haaland, 2009; Jordan and Zvelebil, 2009; Craig et al., 2013; Gibbs and Jordan, 2013; Taché and Craig, 2015), the so called ‘aquatic Neolithic’.

Such a clear and direct relation to the exploitation of aquatic resources could be explained by some intrinsic differences between water and terrestrial related subsistence systems. Aquatic environments provide resources which are rich in nutritious fats or oils. They are constantly available throughout the seasons, but also become particularly accessible and abundant during certain, often short term, periods of the year. These relate to either natural migrations of fish and their spawning or breeding and during the rearing of aquatic mammals. In contrast to traditional game hunting, aquatic resources are particularly rich and easy to catch making them accessible and allowing their exploitation regardless of age and gender. We argue that seasonal intensification of aquatic resource exploitation was facilitated by the introduction of pottery, and together, these prompted increased sedentism and population growth, similar to the model first suggested for the East African early Holocene (Haaland, 2009).

The arrival of pottery did not necessarily transform diets by allowing increased consumption of aquatic foods. It is equally plausible that ceramics simply provided a more efficient way of processing, manipulating and storing oils from fish and other aquatic organisms for consumption and other purposes, thus facilitating intensified, expanded and prolonged use of aquatic resources. The production of aquatic oils for storage may have been particularly important for reducing the need for seasonal migrations. In this way, fishing became incorporated within a broadening subsistence system which allowed a reduction in mobility and a wider range of more specialised practices including pottery production. We can presume that this broadening subsistence system also included exploitation of terrestrial forest products, such as acorns, deer, elk and wild boars, as shown by the faunal assemblages and partially also in the stable isotope data of human bone, but these products were largely excluded from pots implying different processing technologies.

The earliest evidence of fishing nets in North-Eastern Europe are from Karelia (Antrea Korpilahti) and date to the Early Mesolithic (Carpelan, 2008). In Estonia, fishing implements (hooks, fish spears, clubs and harpoons) are known from the Early Mesolithic onwards (Lõugas, 1996a; Bērziņš, 2010), but fishing nets only appear in the Late Mesolithic (i.e. Siivertsi; Rosentau et al., 2013) together with net floats, sinkers, net holding poles and bone needles usable for net production (Lõugas, 1996a; Bērziņš, 2010; Kriiska and Roio, 2011). These technologies appear to coincide with the first pottery use in this region, although taphonomic biases pertaining to the relative preservation of artefact types need to be explored further. Nevertheless, the evidence available supports the notion that pottery was associated with the wider adoption and extensive use of innovative fishing capture techniques.

Together, we suggest that these adaptations allowed larger quantities of fish to be caught and processed in a shorter time and with less labour investment. In turn, more time was dedicated to the production of artefacts, such as pottery, sinkers and nets, in anticipation of these easily exploitable and reliable aquatic resources. This freed up the yearly schedule, required increased residence times and created the conditions for population growth akin to models used for the expansion of the agricultural Neolithic. Stable isotope data of bone collagen from Narva period sites supports limited mobility. Humans buried in coastal sites and inland sites have very different carbon and nitrogen isotope values (Tõrv, 2016; Tõrv and Eriksson, forthcoming), indicating that they subsisted on the local resources rather than extensive coastal/inland migrations in search of resources, which would produce more homogenised isotopic signatures. Whilst difficult to quantify, other studies also support the idea that Northern ceramic ‘hunter-gatherers’ were at high population densities therefore delaying the diffusion of farming to this region compared to others [(Isern and Fort, 2012)](https://paperpile.com/c/sHVo0a/wxNi).

## 5. Conclusions

Organic residue analysis of the earliest pottery vessels in the Eastern Baltic (Narva-type ceramics) shows that they were preferentially used for processing aquatic substances regardless of their typology and the different environmental settings where they were found. Based on these results, we propose that the introduction of ceramic vessels provided a means for more efficient exploitation of coastal and inland fisheries, linked with broadening subsistence systems, increased sedentism and population growth during the Late Mesolithic period. Whether this adaptation was part of a larger super-regional phenomenon that encompasses the entire boreal zone from Siberia to the Western Baltic remains to be seen. To test this hypothesis, a larger synthesis of AMS dates and more widespread organic residue analysis is called for on a much grander scale.

Given our findings, it is vital that the problems associated with the incorporation of ‘old’ carbon from marine and freshwater reservoirs (Kriiska et al., forthcoming) are addressed to decrease the uncertainty of dates made directly on pottery. This is important to more precisely compare the adoption of pottery with changes in the palaeoeconomy, but also to chart the origins and spread of this technology. It has recently been suggested that North-Eastern European pottery may have an origin as far as East Asia, a hypothesis at least consistent with the albeit limited AMS dataset [(Silva et al., 2014)](https://paperpile.com/c/sHVo0a/90VX). If so, the arrival of pottery to the shores of the Eastern Baltic may be part of the same cultural phenomenon adopted by hunter-gatherers living on the shores of the Sea of Japan some 9,000 years earlier.

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Supplementary Data: Appendix A

**Table A.1. List of samples analysed with GC-MS, GC-C-IRMS and EA-IRMS (bulk isotope of charred deposits).** C – Ceramic sherd sample,F – Food crust;i – Internal surface; e – External surface; TÜ/AK – Archaeology collections of the Department of Archaeology, University of Tartu; AI – Archaeology Research Collections of the Tallinn University; PäMu – Archaeology collections of Pärnu Museum. (Cn:x) - carboxilic acids with carbon length n and number of unsaturations x, SFA – saturated fatty acid, UFA – unsaturated fatty acids, DC - α,ω-dicarboxylic acids, ALK – alkanes, APAA - ω-(o-alkylphenyl) alkanoic acids, TMTD - 4,8,12-trimethyltridecanoic acid, pri – pristanic acid, phy – phytanic acid, chol – cholesterol or derivative, abie – dehydroabietic acid, terp – presence of one or several terpenes including α- and β- amyrin, two unidentified isomers of formula C30H48O and an unidentified terpenes of M+ 412, ket – mid chain ketones, ergost – ergostanol, 2-HFA – dihydroxy fatty acid. \* indicates samples from shallow oblong bowls, the rest are from the pointed-base vessels.