Mirva Pääkkönen, Auli Bläuer, Richard P. Evershed & Henrik Asplund

RECONSTRUCTING FOOD PROCUREMENT AND PROCESSING IN EARLY COMB WARE PERIOD THROUGH ORGANIC RESIDUES IN EARLY COMB AND JÄKÄRLÄ WARE POTTERY

Abstract
Based on the dominance of seal and fish bones in the zooarchaeological assemblages the coastal sites of the Comb Ware cultures are generally considered to be settlements of prehistoric seal hunters and fishers. Lipid analyses of food residues in pottery from such sites hold considerable potential to extend understanding of the procurement and processing of these resources. Lipid biomarker and compound-specific stable carbon isotope analyses were conducted on 28 potsherds from a total of 64 Early Comb Ware and Jäkärlä Ware vessels from south-west Finland. The results reveal that even though the Baltic Sea was an important economic resource, terrestrial animals also played an important role in the food cultures of Stone Age coastal dwellers. Thus, combining zooarchaeological data and organic residue analyses on Finnish prehistoric pottery assists in enhancing our understanding on the food procurement strategies of the Neolithic populations of the region, and offer additional possibilities to explore spatial and temporal changes resulting from climatic and/or cultural influences.

Keywords: Organic residue analysis, lipids, fatty acids, compound-specific stable carbon isotopes, Neolithic diet, Finland

Mirva Pääkkönen, Department of Archaeology, University of Turku, FI-20014 Turun yliopisto, Finland and Organic Geochemistry Unit, School of Chemistry, University of Bristol, Cantock's Close, Bristol BS8 1TS, UK: mirva.paakkonen@utu.fi; Auli Bläuer, Department of Archaeology, University of Turku, FI-20014 Turun yliopisto, Finland: auli.blauer@utu.fi; Richard P. Evershed, Organic Geochemistry Unit, School of Chemistry, University of Bristol, Cantock's Close, Bristol BS8 1TS, UK: r.p.evershed@bristol.ac.uk; Henrik Asplund, Department of Archaeology, University of Turku, FI-20014 Turun yliopisto, Finland: asplund@utu.fi.

Received: 14 June 2016; Accepted: 8 August 2016; Revised: 15 September 2016.

INTRODUCTION

The pit-and-comb imprinted vessels originated in the Volga-Kama region and spread to the west at the beginning of the 6th millennium BC. Subsequently, the Upper Volga culture in central Russia developed and created a basis for the rise of Early Comb Ware in the north (Piezonka 2012: 47). Thus, the oldest ceramic type from Finland belongs to the Comb Ware group (Pesonen & Leskinen 2009: 301), which can be further divided into several subgroups (see Table 1). The earliest styles of these groups were the Early Comb Ware in south Finland and Säräisniemi 1 Ware in north Finland (Torvinen 2000; Skandfer 2005). The adaptation of these ceramic vessels and the ability to store and process animal products, such as train oil, was a useful new technology for hunter-gatherer-fishers, since mass hunting of fish and seal played a major role in their seasonal food procurement cycle (Pesonen & Leskinen 2009: 299).

The Early Comb Ware occurred in Finland and in Republic of Karelia (see e.g. Meinander

Ceramic type	Period of use (calBC)
Older Early Comb Ware	5150–4450
Säräisniemi 1 Ware	5100–4350
Younger Early Comb Ware	4450–4150
Jäkärlä Ware	4300–3900
Typical Comb Ware	3950–3500
Late Comb Ware	3750–3250

Table 1. The periodisation of Finnish Stone Age Comb Ware according to Tallavaara et al. (2010).

1984: 29–31; Halinen 2015: 57), while Jäkärlä Ware sites have mainly been found in south-west Finland (Edgren 1966: 15; 1993: 46). The location of Comb Ware dwelling sites is often regarded as related to the optimal use of economic resources. This is especially the case for sites in coastal locations and in archipelagic environments, which have been linked to an increased importance of marine game, i.e. sealing and fishing (e.g. Siiriäinen 1981; 1982; Halinen 2015: 62; cf. Tallavaara & Seppä 2012: 221). Where zooarchaeological material is dominated by seal and fish bones, the sites have been defined as 'clearly seal hunting sites' (Siiriäinen 1982: 19–20).

Animal bones from the Comb Ware sites in Finland consist mainly of burnt bone fragments. Wild mammal, bird, and fish bones have been identified; however, no domestic animal bones dating to this period have been found (Ukkonen 1993; Mannermaa 2003; Bläuer & Kantanen 2013). The Comb Ware culture economy has traditionally been seen as being based mainly on fishing, hunting, and gathering, as direct evidence of cultivation and animal husbandry is absent (e.g. Zvelebil 1981; Núñez 1999). Recently buckwheat (*Fagopyrum esculentum*) and barley-type (*Hordeum*) pollen grains were identified in an Early Neolithic (c 5200–4000 BC) assemblage from south-east Finland and have been interpreted as indicative of early cultivation in that area (Alenius et al. 2013). The early beginning of cultivation has been questioned by Lahtinen & Rowley-Conwy (2013) suggesting there is no reliable evidence of agriculture in Finland before the Iron Age (500 BC).

Zooarchaeological analysis of the bone material from the Comb Ware sites indicates that seals, harp seal (*Phoca groenlandica*), grey seal (*Halichoerus grypus*), and ringed seal (*Phoca hispida*), were the most important game animals especially at coastal sites. Also, the European beaver (*Castor fiber*), Eurasian elk (*Alces alces*), Artic hare (*Lepus timidus*), wild forest reindeer (*Rangifer tarandus fennicus*), and brown bear (*Ursus arctos*) appears to have been hunted along with various fur-bearing carnivores (Ukkonen 1993: 257). Furthermore, it should be noted that the soils in Finland are so acidic that unburnt bone is extremely scarce at prehistoric sites, and even where it does survive, it is usually highly fragmented (Siiriäinen 1981: 11; Ukkonen 1996: 66; 2001: 13).

Organic residue analysis of food residues in archaeological cooking vessels is widely used to identify food procurement, notably the emergence of farming and dairying (see e.g. Evershed et al. 2008a; Dunne et al. 2012; Cramp et al. 2014a). This approach also offers numerous opportunities in Finland, in particular in relation to the cultural traditions and changes in procurement practises of hunter-gatherer-fisher societies and their transition(s) to farming. This is especially important in Finland where it is difficult to discern coherent trends in animal exploitation in prehistory due to the paucity of zooarchaeological remains. Thus, the study of organic residue provides a major opportunity to gain a better understanding of Neolithic animal use in Finland.

Organic residue analyses use a range of lipid biomarker proxies to identify the different commodities being processed in the archaeological vessels. When diagnostic biomarker structures are linked with their $\delta^{13}C$ values, more precise interpretations of the origins of fats can be achieved (Evershed 2008). This proxy is important in tracing changes in food culture. By using the $\Delta^{13}C$ ($\delta^{13}C_{18:0}$-$\delta^{13}C_{16:0}$), different metabolism and biosynthetic origins are emphasised, i.e. fats originating from dairy products can be resolved from ruminant carcass fats. Moreover, non-ruminant fats can be separated from ruminant dairy and carcass fats (Copley et al. 2003: 1526). Fats originating from brackish water or marine organisms have more enriched $\delta^{13}C$ values when compared with the terrestrial fats

(Cramp & Evershed 2014: 326; Pääkkönen et al. in preparation). Additionally, the mixing of fats from different sources can be recognised if the $\delta^{13}C$ values plot between the ranges defined by modern reference fats (Copley et al. 2003: 1526). Unfortunately, most terrestrial mammals, excluding ruminant animals, have similar $\delta^{13}C$ and $\Delta^{13}C$ signatures with freshwater and brackish water fish (Pääkkönen et al. in preparation); hence, the only way of distinguishing between them is to use characteristic aquatic biomarkers.

Since all of the studied sites were located on the Baltic Sea coast, the use of aquatic biomarkers is especially important (for a review see Cramp & Evershed 2014). Several biomarkers have been developed to identify residues originating from fish and marine mammals. The ω-(*o*-alkylphenyl)alkanoic acids (APAAs) are formed from the heating of tri-, di- or mono-unsaturated fatty acids, but they are not formed from saturated fatty acids (Hansel et al. 2004; Evershed et al. 2008b). Phytanic acid and 4,8,12-trimethyltetradecanoic acid (4,8,12-TMTD) are found in low concentrations in terrestrial animals and high concentrations in marine animals (Avigan 1966; Ackman & Hooper 1968). Thus, APAAs with chain lengths C_{18}, C_{20}, and C_{22} should be observed, and at least one of the isoprenoid fatty acids should also be present if the residues originate from aquatic sources (Hansel et al. 2004; Evershed et al. 2008b). In addition, dihydroxy fatty acids (DHYAs) are also considered as biomarkers of aquatic commodities (Hansel & Evershed 2009; Hansel et al. 2011; Cramp & Evershed 2014). Furthermore, the peak area ratio of stearic and palmitic acids ($C_{18:0}/C_{16:0}$) should be < 0.48, since a study of the distribution of the *n*-alkanoic acids in experimentally decomposed lipids has shown that fats originating from fish and mammals can be distinguished using the ratio of $C_{18:0}/C_{16:0}$. It has been suggested that this ratio can be used in detection of aquatic biomarkers if cholesterol and/or at least the two acyclic isoprenoid alkanoic acids, and the C_{16}–C_{20} APAAs are present in the sample (Olsson & Isaksson 2008: 777). However, some caution should be exercised as the relative abundances of fatty acids are affected by differential solubilities and volatilities of homologues in aged fats. Even though findings of cholesterol have been reported from archaeological pottery (see e.g. Berstan et al. 2008; Heron et al. 2015), it has also been suggested that cholesterol could derive from modern contamination (Roffet-Salque et al. in press), rather than from archaeological fats. Thus, we have decided not to include the data of cholesterol in this paper due to the possibility of cholesterol originating from modern handling of the sherds.

Only a handful of examples exist of the investigation of absorbed organic residues of Finnish prehistoric pottery using the afore-mentioned approaches. The most relevant study to this report is the study of Typical/Late Comb Ware to the Late Iron Age performed by Cramp et al. (2014b) of absorbed lipids. Earlier investigations focussed on food crust samples from the Bronze Age Kökar Otterböte site on the Åland Islands in an effort to detect the processing of aquatic commodities (Isaksson 1997), while Comb Ware from Vantaa Maarinkunnas were investigated to determine the origins of organic residues (Hopia et al. 2003). The general conclusion to emerge from the study of absorbed organic residues in Typical/Late Comb Ware is that there was a strong focus on the marine environment as a food source. However, investigations need to be expanded to achieve better chronological and statistical coverage.

Hence, the aim of this study was to investigate a larger collection of Comb Ware vessels than had previously been considered (Hopia et al. 2003; Cramp et al. 2014b) so that more definitive trends in animal exploitation and other aspects of food procurement might be established. The main aims were to determine: (i) what kind of lipid residue survive in the Comb Ware vessels by using the organic residue approach, and (ii) specifically whether biomarkers of aquatic organisms are present, which is crucial as all the studied pottery derive from settlement sites for hunter-gatherer-fisher societies, (iii) whether evidence of dairying is present; (iv) whether relationships exist between the vessel form and rim diameter and the lipid content of the pot, and (v) whether the nature of the absorbed lipids correlates with the zooarchaeological evidence, thereby affirming if the investigation of lipids can provide new information on the exploitation of natural resources during the early stages of the Comb Ware culture. To achieve this, lipid

Fig. 1. All the studied sites are located in south-west Finland; during the Stone Age they were located by the shores of the Baltic Sea. The studied vessels from the Kokemäki Kraviojankangas and the Pomarkku Myllytörmä/Patakoski sites date to the Early Comb Ware period, while the vessels from the Turku Jäkärlä site date to the period of the Jäkärlä Ware. Illustration: M. Pääkkönen.

biomarker and compound-specific stable carbon isotope analyses were performed on potsherds of Early Comb Ware and Jäkärlä Ware from south-west Finland.

MATERIALS AND METHODS

Selection of pottery for organic residues analysis

The material used in this study derives from three different Comb Ware sites in south-west Finland: Kokemäki Kraviojankangas, Pomarkku Myllytörmä/Patakoski and Turku Jäkärlä (Fig. 1). During the Neolithic they were situated on the coast of the Baltic Sea. The Kraviojankangas site was located on an island (Alhonen & Huurre 1991: 151) and is considered to be a seasonal settlement site for seal hunters, due to the high number of seal bones in the zooarchaeological material (Heikkurinen-Montell 1986: 35). The Myllytörmä/Patakoski site was located on the coast on the north shore of a narrowing sound (Alhonen & Huurre 1991: 157); unfortunately the interpretation of the character of the site cannot be discussed as the site has not been published. The Jäkärlä site was also located in the vicinity of the ancient shoreline (Edgren 1966: 68; Asplund 2006), and is a long-term settlement site reflecting different periods of occupation (Europaeus 1926: 59–62; Edgren 1966: 65–76; cf. Laukkanen 1997: 56; Asplund 2006).

The ceramic material from the studied sites is fragmentary, and thus the vessel type cannot be defined with absolute certainty, but all of the studied vessels are likely to have the typical shape of the Comb Ware vessel: the round-bottomed base and the largest rim diameter typically at the rim or just beneath it (see e.g. Edgren 1982: 20–2). Furthermore, two of the sherds from Kraviojankangas and one from Jäkärlä have been AMS-dated. There are also four radiocarbon dates from charcoal found at the sites, one from Jäkärlä and three others from Kraviojankangas. All of the AMS dates for the charcoal from the settlements are in line with the current dates from the food crust (Fig. 2).

A total of 64 Comb Ware sherds from south-west Finland were chosen for this study from the collections of the University of Turku (TYA) and Satakunta Museum (SatM). The number of studied sherds from the Kraviojankangas site was 32, 14 from Myllytörmä/Patakoski, and 18 from the Jäkärlä site (Fig. 3). To prevent sampling the same vessel more than once, sherds were chosen from the rim of the pot or sherds that could be connected to the rim with absolute certainty. The rim sherds or the sherds near the rim were also selected for the study as these are known to yield the highest concentration of lipids (Charters et al. 1993).

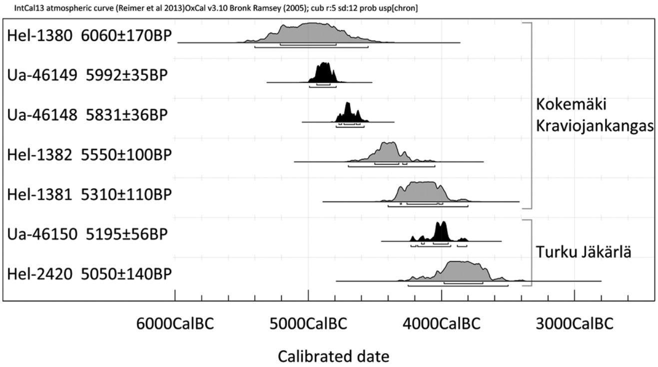

Fig. 2. AMS dates from the crust on the vessels and from charcoal collected during the excavations. The charcoal samples are shown in grey, and the crust samples in black. The AMS-dated food crusts from Kraviojankangas and Jäkärlä are from sherds which were not chosen for GC-C-IRMS or GC/MS analyses. Calibration with the OxCal v3.10 program (Bronk Ramsey 1995; 2001) uses the IntCal13 calibration data (Reimer et al. 2013).

Fig. 3. Examples of rim sherds from Kraviojankangas (TYA 116:980), Patakoski (SatM 18620:10) and Turku Jäkärlä (TYA 313:28). Photos: M. Pääkkönen

Lipid analysis

Sub-samples of surface-cleaned sherds were extracted using a well-established protocol (Evershed et al. 2002; Copley et al. 2003; Cramp et al. 2014a). Briefly, a sub-sample of 2 g of an archaeological potsherd was cleaned with a modelling drill. The sample was crushed and internal standard (*n*-tetratriacontane) was added prior to solvent extraction, using $CHCl_3$/MeOH (2:1 *v/v*). The aliquots of the total lipid extracts (TLEs) were filtered and treated with 40 µl *N*,*O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA, 1 h, 70°C) prior to screening by high temperature-gas chromatography (HTGC). Identification of individual fatty acids was carried out with non-polar gas chromatography-mass spectrometry (GC/MS). In order to prepare the fatty acid methyl esters (FAMEs) from selected sherds, to an aliquot of the sample was added methanolic NaOH (5% *v/v*), the sample was acidified to pH 3 (1 M HCl). The aliquot was extracted with $CHCl_3$. BF_3-MeOH was added and samples extracted with $CHCl_3$ and blown to dryness under N_2. In order to analyse the DHYAs from selected samples, the previously powdered pottery were extracted with direct methanolic acid extraction (Correa-Ascencio & Evershed 2014). Briefly, 5 ml of MeOH/H_2SO_4 (4% *v/v)* was added to solvent extracted powdered sherd samples, samples were heated (70°C, 1 h). Two milliliters of H_2O (double-distilled, DCM extracted) were added to the extract. The supernatant was transferred to a clean culture tube and was extracted with hexane (3 x 2 ml) and blown down under a stream of nitrogen. An aliquot of the extract was treated with 20 µl of BSTFA as described above in readiness for HTGC and GC-MS analyses.

High temperature gas chromatography (HTGC)

HTGC analyses were performed using Agilent Technologies 7890A GC. Diluted samples were introduced by on-column injection. The column was DB-1hT (15 m x 0.32 mm i.d., coated with dimethylpolysiloxane, film thickness, 0.10 µm, Agilent Technologies). The temperature was held isothermally for 2 min at 50°C and increased to 350°C at 10°C/min, followed by isothermal hold at 350°C for 10 min. The flame ionization detector (FID) was set to temperature 350°C. Helium was used as a carrier gas and maintained at constant flow of 4.6 ml/min. The peaks were identified by the retention times and quantification was achieved using the internal standard method.

Gas chromatography-mass spectrometry (GC/MS)

GC/MS analyses of TLEs were performed using a Finnigan Trace MS quadrupole mass spectrometer coupled to a Trace GC. Diluted samples were introduced using a PTV injector in the splitless mode onto a HP-1 (50 m x 0.32 mm i.d. fused-silica capillary column coated with dimethylpolysiloxane, film thickness, 0.17 µm, Agilent Technologies). The GC oven temperature was programmed from 50°C, following an isothermal hold for 2 min, to 300°C at 10°C/min, followed by an isothermal hold at 300°C for 10 min. Helium was used as carrier gas and maintained at constant flow 5 ml/min. The MS was operated in electron ionization (EI) mode (70 eV) with GC/MS interface temperature of 250°C and a source temperature of 200°C. The emission current was 50 µA, and the MS was set to acquire in the range *m/z* 50-650 Daltons at two scans per second. Peaks were identified on the basis of their mass spectra using Thermo Xcalibur 3.0.63 software.

The structural identification of APAAs was carried out with polar GC/MS (VF-23ms, 60 m x 0.32 mm i.d. fused-silica capillary column coated with cyanopropyl film thickness, 0.15 µm, Agilent Technologies). The initial oven temperature was 50°C held isothermally for 1 min, followed by a programme from 50°C to 250°C at 10°C/min, then an isothermal hold at 250°C for 10 min. The MS was operated in EI mode (70 eV) with GC/MS transfer line temperature of 250°C and ion source temperature of 200°C. Specific ions for APAAs were detected using selected ion monitoring (GC/MS-SIM, scanning for ions *m/z* 105, 262, 290, 318, and 346). The structural identification of DHYAs was carried out with non-polar GC/MS (HP-1, 50 m x 0,32 mm i.d. fused-silica capillary column, coated with dimethylpolysiloxane, film thickness, 0.17 µm, Agilent technologies and RTX-1, 50 m x 0.32 mm i.d. fused-silica capillary column

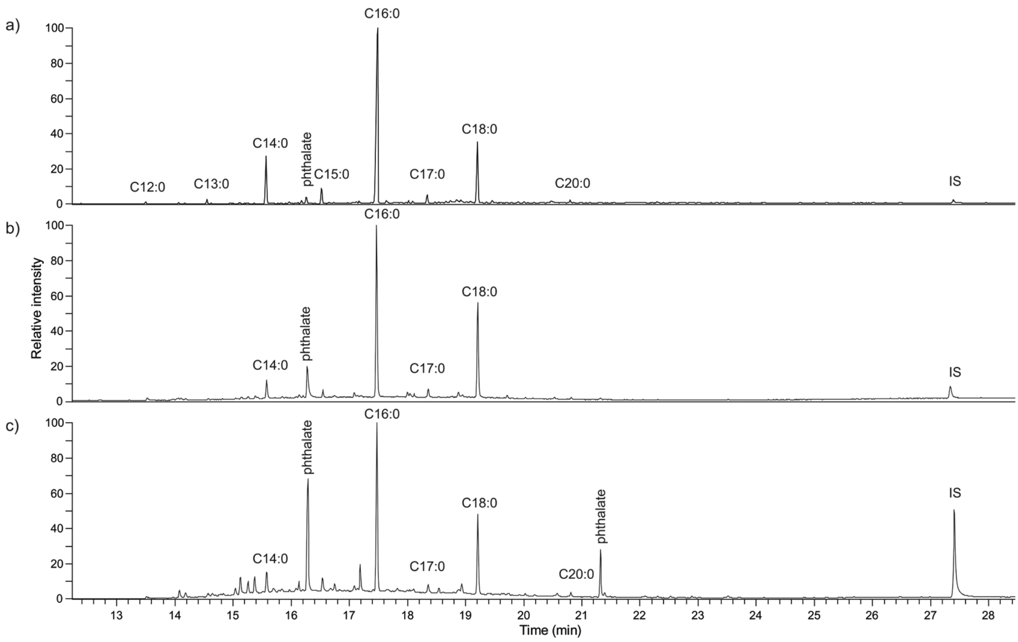

*Fig. 4. Partial GC-chromatograms of vessels from a) Kraviojankangas; b) Myllytörmä/Patakoski; and c) Jäkärlä show similar fatty acid distributions. IS denotes an internal standard (*n*-tetratriacontane).*

coated with dimethylepolysiloxane, film thickness, 0.17 µm, Restek). The MS was operated in EI mode (70 eV) with GC/MS transfer line temperature of 300°C and ion source temperature of 300°C The initial GC oven temperature was held at 50°C for 1 min followed by a temperature programming from 50°C to 300°C at 10°C/min, followed by an isothermal hold at 300°C for 10 min. Specific ions for DHYAs were detected using SIM mode (scanning for ions *m/z* 159, 187, 215, 243, 259, 287, 315, 443, 471, 499).

Gas-chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS)

The isotope compositions of the $C_{16:0}$ and $C_{18:0}$ fatty acids were determined using gas chromatography-combustion-isotope ratio mass spectrometry (GC-C-IRMS). Stable carbon isotope values of fatty acid methyl esters were determined using an Agilent Technologies 7890A GC coupled to an IsoPrime 100 (70 eV, three faraday cup collectors *m/z* 44, 45, and 46) via an IsoPrime GC5 combustion interface with a CuO and silver wool reactor maintained at 850°C. Diluted samples were introduced using a PTV injector in the splitless mode onto a HP-1 (50 m x 0.32 mm i.d. fused-silica capillary column coated with dimethylpolysiloxane, film thickness, 0.17 µm, Agilent Technologies). The GC oven temperature was programmed from 40°C, following an isothermal hold for 1 min, to 300°C at 10°C/min, followed by an isothermal hold at 300°C for 10 min. Each sample was run as a duplicate.

Statistical treatment of the data

Spearman's correlation coefficient (r_s) was used to establish possible differences between the lipid concentrations and vessel rim diameter and rim type.

RESULTS

Absorbed lipid residue analyses

Out of the 64 sherds analysed well-preserved lipids (concentration > 5 µg/g) were detected by FID-GC in 56 vessels. These residues were shown by GC/MS to be composed primarily of $C_{16:0}$ and $C_{18:0}$ acids (Fig. 4), making them appropriate candidates for compound-specific stable carbon isotope analysis by GC-C-IRMS. Of the studied samples, 28 were analysed using GC-C-IRMS; 13 from Kraviojankangas, 10 from Myllytörmä/Patakoski, and five from Jäkärlä (Table 2).

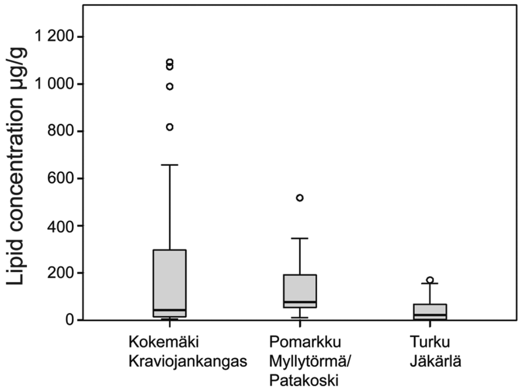

Fig. 5. Box plot showing the lipid concentrations in potsherds from the sites invesigated.

The Jäkärlä Ware vessels contained lower concentrations of organic residues than were found in the other Comb Ware vessels studied (Fig. 5). The lipid concentration in Kraviojankangas varied between 5–1093 µg/g: 11–518 and 0–170 µg/g in Myllytörmä/Patakoski and Jäkärlä, respectively (Tables 2 & 3). Even though the lipid concentrations were higher at Kraviojankangas, only five vessels from the site contained lipids in concentrations > 500 µg/g, and the median of the concentration does not differ significantly between the sites (43, 77, and 22 µg/g in Kraviojankangas, Myllytörmä/Patakoski and Jäkärlä, respectively; Fig. 5).

GC/MS and SIM, and GC-C-IRMS analyses showed none of the studied vessels contained all molecular or carbon isotope proxies available for the detection of processing aquatic commodities. Thus, a combination was used, which together still provide unequivocal evidence of a processing of aquatic organisms in the vessels. In terms of actual use of vessels the possibility of cooking and/or processing/storage of aquatic

Catalogue number / site	Lab. code	Rim type	Rim diam. (cm)	Lipid conc (µg/g)	$\delta^{13}C_{16:0}$	$\delta^{13}C_{18:0}$	$\Delta^{13}C$	$C_{18:0}/C_{16:0}$	Biomarker composition	Interpretation
Kokemäki Kraviojankangas										
TYA 116:365. 876	CC1	1	34	245.8	-26.3	-25.7	0.6	0.22	none	Aquatic?
TYA 151:1331	CC5	1	38	211.9	-26.2	-25.8	0.5	0.24	C_{18}–C_{20} APAAs. TMTD. Pris. Phy. DHYAs?	Aquatic
TYA 151:1357	CC6	2	30	224.9	-24.1	-25.8	-1.7	0.45	DHYAs	Aquatic?/Ruminant (wild forest reindeer)?
TYA 116:620	CC8	1	20	817.8	-29.1	-30.8	-1.7	0.67	none	Ruminant (Eurasian elk)
TYA 116:896	CC11	2	21	429.1	-25.3	-24.3	1.0	0.30	C_{16}–C_{20} APAAs. TMTD. Phy	Aquatic
TYA 116:686	CC14	1	24	44.2	-26.1	-26.8	-0.7	0.41	C_{18} APAAs	Aquatic?/Ruminant (wild forest reindeer)?
TYA 151:1357	CC15	3	14	1092.6	-26.3	-28.3	-2.0	0.41	C_{16}–C_{18} APAAs. TMTD. Phy. DHYAs	Aquatic/Ruminant (Eurasian elk/wild forest reindeer)?
TYA 116:969. 984	CC16	1	34	1073.5	-26.5	-27.9	-1.4	0.03	C_{18} APAAs. TMTD. Phy. DHYAs?	Aquatic/Ruminant (Eurasian elk/wild forest reindeer)?
TYA 116:825. 1005	CC17	2	25	425.0	-26.0	-25.9	0.2	0.26	C_{16}–C_{20} APAAs. DHYAs	Aquatic?
TYA 116:518. 1051. 1165	CC20	2	34	135.2	-24.7	-26.1	-1.4	0.85	C_{18} APAAs. Phy	Aquatic?/Ruminant (wild forest reindeer)?
TYA 151:1331	CC23	1	22	658.1	-24.7	-24.7	-0.1	0.39	C_{16}–C_{20} APAAs. TMTD. Phy. DHYAs	Aquatic
TYA 116:742	CC25	1	30	116.1	-26.8	-29.2	-2.4	0.94	C_{18} APAAs. TMTD. Phy	Ruminant (wild forest reindeer)/Aquatic?
TYA 151:1331	CC26	1	22	989.4	-25.3	-24.7	0.6	0.86	Phy	Aquatic?
Pomarkku Myllytörmä/Patakoski										
SatM 18620:10	CC33	1	32	192.2	-26.7	-28.7	-2.0	0.58	C_{16}–C_{20} APAAs. C_{22} APAAs?. TMTD. Phy. DHYAs?	Aquatic
SatM 18620:11	CC34	1	28	29.8	-26.2	-28.6	-2.4	0.26	C_{18} APAAs. DHYAs	Aquatic?/Ruminant (wild forest reindeer)?
SatM 18620:6	CC35	3	45	252.2	-25.8	-28.4	-2.7	0.59	C_{16}–C_{18} APAAs	Ruminant (wild forest reindeer)/Aquatic?
SatM 18620:18	CC36	1	46	10.7	-26.4	-29.6	-3.2	0.86	C_{18} APAAs	Ruminant (wild forest reindeer)
SatM 18620:7	CC37	1	36	517.8	-26.8	-30.0	-3.2	0.39	none	Ruminant (Eurasian elk)
SatM 18620:14	CC38	2	35	58.7	-26.4	-28.0	-1.7	0.39	C_{16}–C_{18} APAAs. Phy	Aquatic?/Ruminant (Eurasian elk/wild forest reindeer)?
SatM 18620:29	CC39	1	37	170.8	-26.1	-28.8	-2.7	0.66	C_{18} APAAs. DHYAs	Aquatic?/Ruminant (Eurasian elk/wild forest reindeer)?
SatM 18620:50	CC42	1	10	345.7	-28.9	-30.3	-1.4	0.70	none	Ruminant (Eurasian elk)
SatM 18620:17	CC44	2	23	70.5	-25.7	-26.7	-1.0	0.15	C_{16}–C_{18} APAAs	Aquatic?/Ruminant (wild forest reindeer)?
SatM 18620:48. 49	CC45	1	30	171.8	-27.0	-26.1	0.9	0.21	none	Aquatic?

Turku Jäkärlä										
TYA 194:11	JAK4	2	17	27.5	-27.0	-26.5	0.5	0.42	Pris. Phy	Aquatic?
TYA 313:28	JAK7	1	20	67.4	-26.9	-26.4	0.5	0.28	C_{18} APAAs. TMTD. Pris. Phy	Aquatic?
TYA 313:38	JAK11	4	13	155.6	-27.1	-26.0	1.1	0.74	none	Aquatic?
TYA 194:58	JAK15	1	27	170.2	-26.4	-25.5	0.9	0.31	C_{18} APAAs	Aquatic?
TYA 208:35	JAK18	2	23	97.6	-27.9	-30.1	-2.2	2.05	C_{18} APAAs?	Ruminant (Eurasian elk)

Table 2. Description of all of the sherds analysed with summaries of GC, GC/MS and GC-C-IRMS findings. The rim types in the studied vessels are divided into four groups: straight (1), slightly inwards bent (2), profiled (3), and narrowing toward the rim (4) (see also Fig. 8). The following abbreviations are used to describe the biomarker composition of the vessels: APAAs – ω-(o-alkylphenyl)alkanoic acids; TMTD – 4,8,12-trimethyltridecanoic acid; Phy – phytanic acid; Pris – pristanic acid, DHYA – dihydroxy acids; ? – uncertain identification of the biomarker due to low concentration; none – absence of the targeted biomarkers in vessels. Furthermore, in the interpretation column 'Aquatic?' indicates those samples with an incomplete set of aquatic biomarkers but which are still likely to contain fats from aquatic sources based on carbon isotope composition. For example, samples with a high $\Delta^{13}C$ value (> -1) are considered possibly aquatic if the $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ support the identification, even if the aquatic biomarker composition was incomplete. Likewise, extracts with a possible ruminant contribution are marked with 'Ruminant? '. See also Table 4.

products are both considered the most likely uses of the vessels.

The cooking and/or processing/storage of products of aquatic origin in a vessel is confirmed if following criteria are fulfilled: (i) APAAs with chain-length of C_{16}–C_{20}, DHYAs, and at least one of the three isoprenoid fatty acids were detected; and (ii) the ratio of $C_{18:0}/C_{16:0}$ is < 0.48. Only one vessel yielded an extract fulfilling all these criteria, CC23 (Table 2). However, a number of other vessels were confirmed as having been used in the cooking and/or processing/storage of aquatic products based on the isotopic composition. For example, the carbon isotopic composition of JAK11 points to aquatic origin, nonetheless, no aquatic biomarkers detected. Another example is CC35 where the $\Delta^{13}C$ value and $C_{18:0}/C_{16:0}$ ratio point towards ruminant origin of the fats, but the C_{16}–C_{18} APAAs and $\delta^{13}C_{16:0}$ and $\delta^{13}C_{18:0}$ values could also suggest an origin from brackish water organism(s) and thus the sample is labelled as a mixture of ruminant and possibly aquatic fats (see Table 2).

Based only on the carbon isotope values, most of the degraded fats likely originated from brackish water dwelling organisms, i.e. from the Baltic Sea (Fig. 6), nevertheless, many of these vessels could also contain fats of wild ruminants such as forest reindeer, since the $\delta^{13}C$ values of brackish water species and reindeer/wild forest reindeer overlap (Pääkkönen et al. in preparation). All of the studied extracts failed to show APAAs ranging from C_{18}–C_{22} chain lengths, although one sample contained C_{16}–C_{20} APAAs and possibly APAAs with chain length C_{22} (Fig. 7). However, 12 samples contained either 4,8,12-TMTD, phytanic or pristanic acid and extracts of nine vessels contained DHYAs, although some were only present in low concentrations. Thus, fats that possibly originated from aquatic organisms were found in 12 vessels from the Kraviojankangas site, seven samples from Myllytörmä/Patakoski and four samples from the Jäkärlä site (Table 2).

Based on the $\delta^{13}C$ values, the animal fats from the Kraviojankangas pottery mostly originated from brackish water dwelling organisms (Fig. 6); although two of the vessels (CC8 and CC25) contained ruminant fats, CC8 likely to derive from Eurasian elk and CC25 from wild forest reindeer. Interestingly, vessel CC25 also

Catalogue number / site	Lab. code	Rim type	Rim diam. (cm)	Lipid conc µg/g)
Kokemäki Kraviojankangas				
TYA 151:1357	CC2	1	8	4.5
TYA 116:980	CC3	1	26	37.3
TYA 116:717, 718	CC4	2	25	6.8
TYA 151:1331	CC7	1	13	20.2
TYA 116:977	CC9	1	19	32.1
TYA 151:1204	CC10	2	20	42.6
TYA 116:836	CC12	1	23	59.2
TYA 116:444	CC13	1	23	24.9
TYA 116:742	CC18	1	24	9.4
TYA 151:1224	CC19	3	30	347.4
TYA 151:1357	CC21	3	30	5.0
TYA 151:1331	CC22	3	31	7.2
TYA 151:1357	CC24	1	23	10.5
TYA 151:1331	CC27	3	32	21.5
TYA 151:1186	CC28	1	18	30.8
TYA 151:1331	CC29	3	18	6.5
TYA 151:216	CC30	3	23	31.4
TYA 151:1331	CC31	1	25	6.5
TYA 116:734	CC32	1	15	55.2
Pomarkku Myllytörmä/Patakoski				
SatM 18620:28	CC40	1	22	76.2
SatM 18620:21	CC41	1	23	54.1
SatM 18620:2	CC43	1	30	25.5
SatM 18620:27	CC46	2	27	78.5
Turku Jäkärlä				
TYA 208:35	JAK1	1	17	30.6
TYA 208:57	JAK2	4	11	19.8
TYA 194:73	JAK3	1	21	0.0
TYA 194:8	JAK5	1	15	27.1
TYA 194:37	JAK6	4	20	2.1
TYA 208:48	JAK8	1	n/a	24.8
TYA 313:36	JAK9	1	25	8.4
TYA 313:72	JAK10	2	n/a	15.1
TYA 208:187	JAK12	1	10	0.0
TYA 313:49	JAK13	4	17	0.0
TYA 313:40	JAK14	1	26	2.6
TYA 194:28	JAK16	1	20	0.0
TYA 194:46, 47, 48	JAK17	1	35	76.1

Table 3. Description of the sherds which were not analysed by GC, GC/MS and GC-C-IRMS. The rim types in the studied vessels are divided into four groups: straight (1), slightly inwards bent (2), profiled (3), and narrowing toward the rim (4) (see also Fig. 8).

contained aquatic biomarkers. Five other vessels also contained fats that could derive either from wild forest reindeer and/or from aquatic sources (Table 4). The distribution of $\delta^{13}C$ values from the Myllytörmä/Patakoski site was different to Kraviojankangas, with the majority of the vessels having $\delta^{13}C$ values that plot between the range of Eurasian elk and brackish water species (Fig. 6), and can be considered to be the result of mixing of commodities in vessels (cf. Copley et al. 2003: 1526). Three of the vessels contained evidence of fats of aquatic origin, but based on $\delta^{13}C$ values, contained fats likely to originate from mixing of brackish water and wild ruminants. Fats extracted from vessel CC35 likely derive from wild forest reindeer, but could also contain a contribution from aquatic sources. One vessel contained residues with carbon isotope values that appear to derive purely from organisms dwelling in brackish water, while four other vessels contained fats originating from predominantly ruminant animals (Fig. 6; Table 4). The same pattern can be seen from the $\Delta^{13}C$ distribution; eight extracts had $\Delta^{13}C$ values similar to ruminant animals, while four of these samples could possibly contain contributions from aquatic organisms (Fig. 6). Only one sample from the Jäkärlä site contained fats originating from ruminant animals, with all the other extracts likely originating from the Baltic Sea organisms. There was no evidence for the mixing of ruminant and brackish water organisms in the Jäkärlä Ware vessels (Fig. 6). Importantly, no evidence of dairy fats was detectable in any of the vessels investigated.

Correlating lipid concentrations and vessel rim diameter and rim type

Since the vessel form is likely to be uniform, attention was placed on the rim diameter and rim type. The rim diameter of the studied

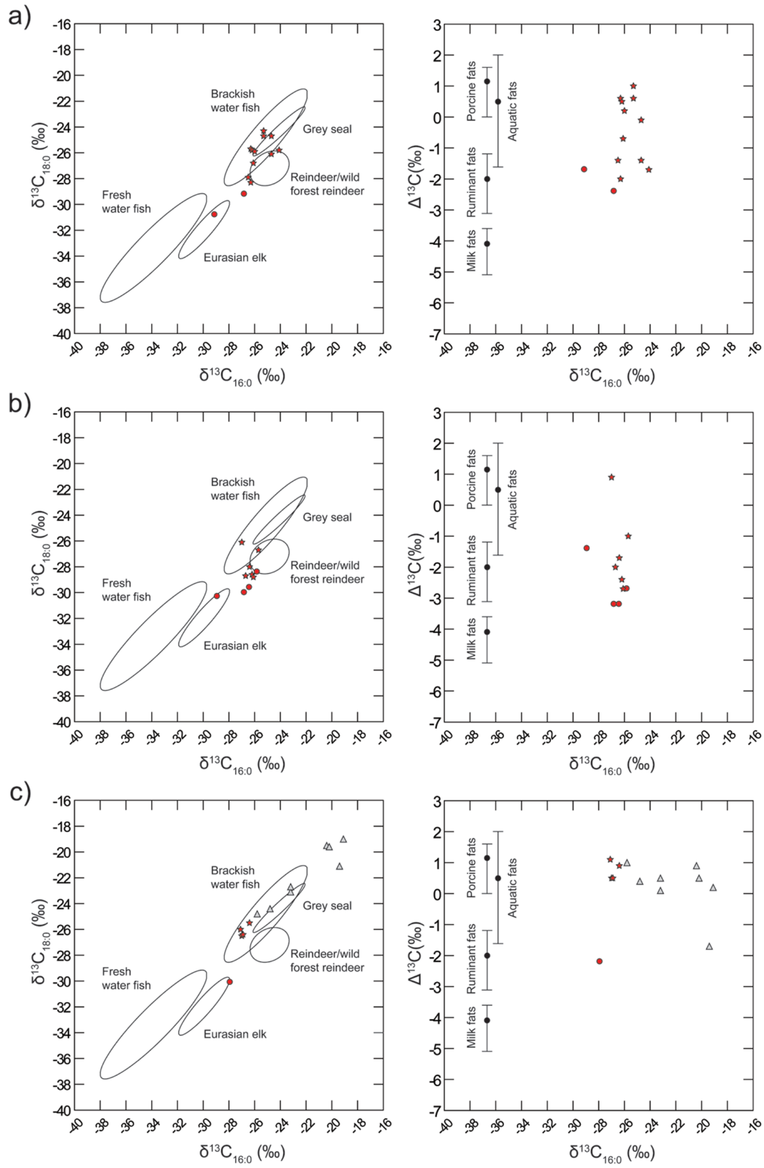

Fig. 6. The $\delta^{13}C$ and $\Delta^{13}C$ ($=\delta^{13}C_{18:0}$-$\delta^{13}C_{16:0}$) plots of vessels from Kraviojankangas and Myllytörmä/ Patakoski (a and b, respectively) show both the mixing of terrestrial and brackish water fats; c) the $\delta^{13}C$ and $\Delta^{13}C$ plots of Jäkärlä Ware and Typical/ Late Comb Ware (Cramp et al. 2014b, shown as triangles). The vessels represented by stars indicate the possible presence of aquatic fats in the residue, the circles represent vessels with fats originating from ruminant sources; in addition, all of the Typical/ Late Comb Ware vessels contained aquatic biomarkers. The confidence ellipses derived from modern reference fats collected from Finland and the Baltic Sea (Pääkkönen et al. in preparation).

vessels from Kraviojankangas ranged between 8–38 cm, and 10–46 cm in Myllytörmä/Patakoski; in Jäkärlä Ware the diameter ranged between 10–35 cm. No correlation was observed between the rim diameter and lipid concentration (Fig. 8; $r_s = 0.110$, $p = 0.550$; $r_s = 0.015$, $p = 0.958$; $r_s = 0.234$, $p = 0.383$; in Kraviojankangas, Myllytörmä/Patakoski and Jäkärlä, respectively). The rim types of the studied vessels can be divided into four different categories; straight, slightly inwards bent, profiled, and narrowing toward the rim of the vessel. The fourth rim type appears only in Jäkärlä Ware vessels, and rim type 1 was the most common at all the studied sites. Rim type 3 is absent in Jäkärlä Ware and rare at the Myllytörmä/Patakoski site. Moreover, rim type does not correlate with the organic residue concentration of the vessel (Fig. 8; r_s =-0.091, p = 0.620; r_s = 0.086, p = 0.770; r_s = 0.013, p = 0.961; in Kraviojankangas, Myllytörmä/Patakoski and Jäkärlä, respectively).

Site/Interpretation	Aquatic	Aquatic?	Aquatic /Ruminant?	Aquatic? /Ruminant?	Ruminant	Ruminant /Aquatic?
Kokemäki Kraviojankangas	3	3	2	3	1	1
Pomarkku Myllytörmä/Patakoski	1	1	0	4	3	1
Turku Jäkärlä	0	4	0	0	1	0

Table 4. Interpretation of the vessels based on GC, GC/MS and GC-C-IRMS analyses according to sites. Uncertain identification is shown with '?'. Samples identified with 'Aquatic?/Ruminant?' can originate from either sources, whereas fats of samples identified as 'Ruminant/Aquatic?' are more likely to originate from ruminant sources than aquatic sources. See also Table 2.

DISCUSSION

Lipid residues and Comb Ware economy

The results of this study support the view that the economy of the Comb Ware culture was based on hunting, fishing and gathering.

The bone material from the sites included in this study consisted of typical Stone Age settlement site fauna (Table 5), and the $\delta^{13}C$ values of the studied Early Comb Ware sites were consistent with the zooarchaeological material; over 95% of the identifiable bone material consisted of seal and fish, when 74% of the vessels with identifiable fatty acid content showed the likely or possible presence of aquatic fats as the main component of fat content (Table 4). Furthermore, the $\delta^{13}C$ values from the Kraviojankangas site were more enriched than those from the Myllytörmä/Patakoski site. Contrary to the Myllytörmä site, the bones of terrestrial mammals, including the bones of European beaver and possible elk bones, were found at the Kraviojankangas site (Table 3). By visual inspection of Fig. 6, the mixing of ruminant fats and aquatic fats seems to have been more common in Myllytörmä/Patakoski than in Kraviojankangas. This finding is inconsistent with the zooarchaeological analyses, since based on the bone material, more fats originating from terrestrial sources should have been detected from Kraviojankangas than from Myllytörmä/Patakoski. However, it needs to be taken into account that the assemblage of identified zooarchaeological material from Kraviojankangas was 16 times larger than that from the Myllytörmä site.

The vessels from the Jäkärlä site have a similar distribution of $\delta^{13}C$ values to those of the Kraviojankangas site, and all but one extract displayed $\delta^{13}C$ and $\Delta^{13}C$ values consistent with the fats of brackish water organisms. Furthermore, based on the $\delta^{13}C$ values, the economy at the Jäkärlä site was possibly even more biased to the Baltic Sea than the economy at Kraviojankangas. While this does not appear to concur with the zooarchaeological evidence, which points to a more terrestrial-based economy at Jäkärlä than the Early Comb Ware sites studied, it must be noted that the faunal record is sparse with only 25 identified bone fragments (Table 5).

The different spatial locations of the Early Comb Ware sites could explain the differences in the $\delta^{13}C$ and $\Delta^{13}C$ values of the fats in the vessels. Since the Myllytörmä/Patakoski site was located on the shore rather than on an island, its inhabitants probably had better access to large terrestrial game species than the people living on the island where the Kraviojankangas site was located, leading to the inhabitants exploiting the Baltic Sea as their major food source. It also has to be taken into consideration that the differences between these two sites could be explained by the seasonal sedentarism being practiced by the Comb Ware people.

The lack of aquatic biomarkers, especially APAAs ranging from C_{18}–C_{22}, at all of the studied sites is interesting. These biomarkers are present at the Maarinkunnas and Stenkulla sites (Cramp et al. 2014b: Table 1), but especially APAAs with the chain length C_{22} are not found at any of the studied sites, with one possible exception from Myllytörmä/Patakoski, even though the $\delta^{13}C$ values indicate the Baltic Sea was the origin of the fats. It is not clear why this difference exists, but perhaps (i) the soils at the sites have preserved the lipids differently, (ii) the ceramic matrix in the vessels is different, (iii) the vessels experienced difference heating regimes, as APAAs only form at very high temperatures (c 270°C), i.e. in excess of boiling temperatures, or (iv) there could have been other differences in the ways of food procurement and preparation (i.e. drying, smoking, fermenting, or eating fish raw could have been more common than cooking).

Dating of the sites

Two vessels from Kraviojankangas were AMS-dated (CC20; Ua-46148 and CC3; Ua-46149) as well as one vessel from Jäkärlä (JAK15; Ua-46150). The crusts from Kraviojankangas dated in between the dated charcoal samples (Hel-1380, Hel-1381, Hel-1382; Jungner & Sonninen 1983) from the dwelling site. Charcoal from Jäkärlä (Hel-2420; Jungner & Sonninen 1996) dated slightly younger than the crust from the vessel (Fig. 2). However, the reservoir effect can affect radiocarbon dates of carbonaceous residues with inputs from the Baltic Sea (e.g. Lougheed et al. 2013). The fats in the studied vessels mainly originated from the Baltic Sea, and thus the older radiocarbon dates of the food crusts compared to the charcoal samples could be due to the reservoir effect. In the early 1980s thermoluminescence (TL) dates of eight sherds from Kraviojankangas ranged from 6670±390 to 4270±860 BP (Janér 1983: 6). Some of the dates were thus younger than the ones presented in Fig. 2, which could also, in principle, indicate the existence of a reservoir effect in the AMS dates obtained from food crusts. Nevertheless, it should be noted that the accuracy of TL-dates was ±10% (Janér 1983: 7), so the results should only be seen as approximate. Furthermore, it should be noted that all of the charcoal samples are from different contexts than the studied sherds, so caution is needed when interpreting the AMS dates of the sites studied.

Environmental conditions and a comparison of the lipids from the Early Comb Ware and Typical/Late Comb Ware vessels

In the $\Delta^{13}C$ plot, the residues that plot more to the right-hand side are interpreted as containing a greater marine component (Copley et al. 2004: Fig. 4). Interestingly, compared to the previous study (Cramp et al. 2014b), the vessels from Myllytörmä/Patakoski and the Jäkärlä sites did not show as strong an influence from the Baltic Sea as the vessels from the Typical/Late Comb Ware periods (Fig. 6). During the Comb Ware period, the salinity of the Baltic Sea was slightly higher than it is currently, i.e. 13‰ in the central parts of the basin and 8‰ in the north (Leppäranta & Myrberg 2009: 11). However, there

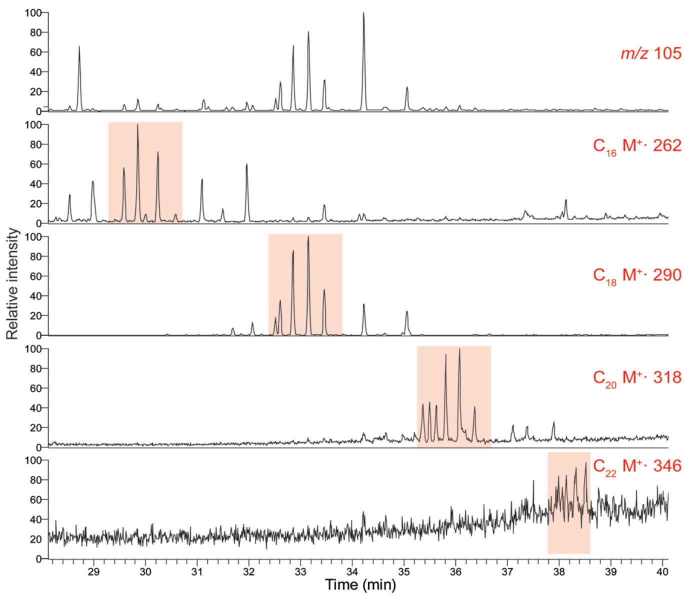

Fig. 7. Partial total ion current (TIC) obtained from the FAME fraction of CC33 (SatM 18620:10), showing the base peak m/z 105 of the APAAs and the distribution of the APAAs ranging from chain lengths C_{16}, C_{18}, and C_{20} (M+· 262, M+· 290, and M+· 318, respectively); the chain length C_{22} (M+· 346) is possibly present in this fraction, but is absent in all of the studied samples. The presence of the APAAs are evidence of the processing of aquatic commodities in the vessel.

Species	KK	PM	TJ
Seal (*Phocidae*)	1063	65	14
Burbot (*Lota lota*)	2		
Northern pike (*Esox lucius*)	8		
Perch (*Perca fluviatilis*)	4		
Perch/Pikeperch (*Sander lucioperca*)	4		
Carp family (Cyprinidae)	2		1
Salmon family (Salmonidae)		1	
Fish	3	5	4
Eurasian elk (*Alces alces*)	1		
Elk?	11		
Artic hare (*Lepus timidus*)	6		1
European beaver (*Castor fiber*)	25		3
Beaver?	1		1
Red squirrel (*Sciurus vulgaris*)	1		
Brown bear (*Ursus arctos*)	1		
Otter? (*Lutra lutra*?)	1		
Pine marten? (*Martes martes*?)	2		
Red fox? (*Vulpes vulpes*?)	1		
Bird	3		1

Table 5. Bone material (NISP, Number of identified specimens) from the sites included in this study are: Kokemäki Kraviojankangas (KK) (the National Museum of Finland, KM 20584; Fortelius 1980a), Pomarkku Myllytörmä (PM) (KM 9560; Fortelius 1980b), Turku Jäkärlä (TJ) (TYA 194, 208, 313, 336, 416, 427, 457, 559, 615; Vormisto 1985; Bläuer 2015). The analysed bone material from Kokemäki Kraviojankangas (KM 20584) and Pomarkku Myllytörmä (KM 9560) are from different excavation years than the pottery subject of this study. Turku Jäkärlä is a multi-period site with pottery also from other periods than Jäkärlä. No analyses have been carried out for the bone material from Patakoski.

should not have been any increase in salinity between the Early Comb Ware and the Typical/Late Comb Ware periods, rather the salinity of the basin decreased towards the Typical/Late Comb Ware period (Gustafsson & Westman 2002: Fig. 4). Usually the inflow from the North Sea is continuous with moderate salinities, but aperiodically strong and highly saline pulses, called Major Baltic Inflows, do occur (Leppäranta & Myrberg 2009: 158). Thus, one explanation for the more marine $\Delta^{13}C$ values from the Typical/Late Comb Ware vessels could be the processing of fish or seal caught from the Baltic Sea after saline water exchange coming from the North Sea. Another possible explanation could be the salinity gradient of the Baltic Sea. Even in the modern day, the Finnish Archipelago Sea has a broad-scale surface water salinity gradient that ranges between 4–6‰ (see e.g. Sjörs et al. 2004: 60; Leppäranta & Myrberg 2009: 265; Suominen et al. 2010: 224). These salinities do not notably differ from the salinities of the Finnish shores in the Gulf of Finland (Andrejev et al. 2004: 7). Unfortunately, the modern salinities are not comparable to the Stone Age salinities due to post-glacial rebound and changes in the archipelago environment and riverine inflows.

The distributions of the $\delta^{13}C$ values of the Jäkärlä Ware and the Typical/Late Comb Ware both show the importance of the Baltic Sea to the studied cultures. The Typical Comb Ware sites and Jäkärlä Ware dwelling sites were probably chosen by the settlers based on similar criteria. This is supported by that fact that at some sites ceramics from both cultures are present (Alhonen & Huurre 1991: 174). Thus, it is not surprising that the food resources were similarly exploited in both cultures, but of course it still has to be taken into account that such similarities can also originate from cultural factors rather than the environment.

CONCLUSION

The Comb Ware dwelling sites located on the coast of the Baltic Sea are traditionally considered as having been orientated towards a marine subsistence. However, even though the faunal assemblages are dominated by seal and fish bones, the organic residue evidence shows that ruminant animals were also important to Early Comb Ware and Jäkärlä Ware people.

The studied sherds from the Early Comb Ware sites, Kraviojankangas, and Myllytörmä/Patakoski, show a mix of aquatic and ruminant product processing. Contrary to the zooarchaeological material, the mixing of fats points to the processing of both terrestrial and aquatic organ-

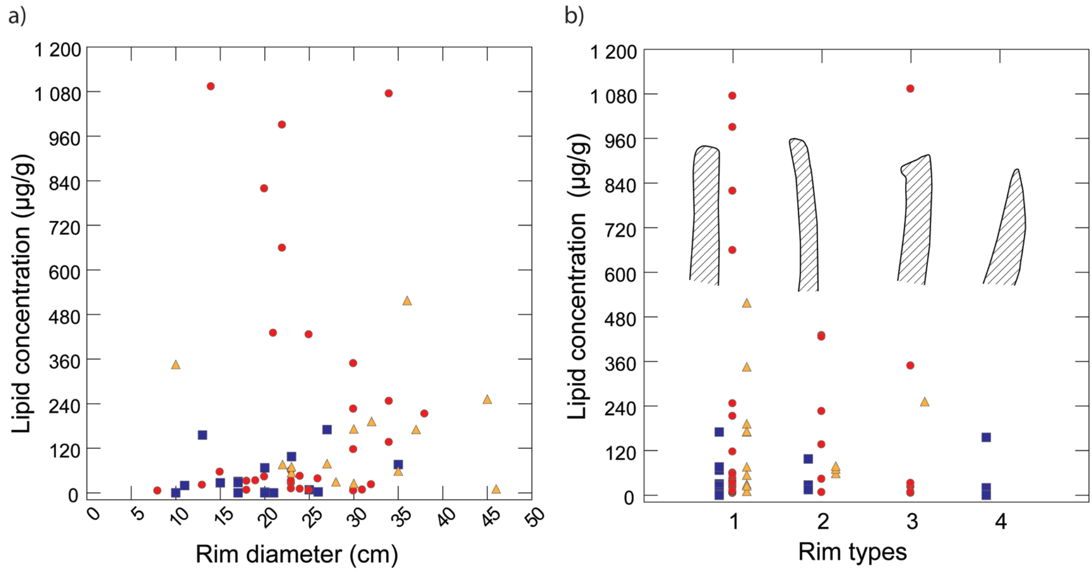

Fig. 8. a) Rim diameters and lipid concentrations of the vessels; b) the correlation between rim types and lipid concentrations of the vessels. Early Comb Ware from Kraviojankangas and Myllytörmä/Patakoski shown as circles and triangles, respectively. Jäkärlä Ware vessels from Turku Jäkärlä shown as squares.

isms, which seems to have been more common at Myllytörmä/Patakoski than at Kraviojankangas. Moreover, comparing the findings obtained with the zooarchaeological data, supports the interpretation of the Kraviojankangas site as a seal hunter settlement. Furthermore, the Jäkärlä Ware contained residues of fats that mostly originated from Baltic Sea organisms, even though the zooarchaeological assemblages also contained terrestrial animals. This underscores the importance of using both zooarchaeological material and organic residues analysis of pottery, i.e. lipid biomarkers and $\delta^{13}C$ values, in order to gain a better understanding of the animal exploitation at prehistoric sites in Finland.

The previous, smaller scale study by Cramp et al. (2014b) on Finnish Typical/Late Comb Ware vessels did not show any evidence of mixing ruminant and aquatic fats, as was found to be commonplace in this new investigation. The vessels subject of the earlier study, were younger than those examined here, so it may be possible that this difference could simply be due to different ecological and environmental patterns at the different the sites. However, it cannot be ruled out that the Typical/Late Comb Ware culture was more oriented toward using the Baltic Sea as a resource for food and other commodities than the Early Comb Ware cultures.

Based on this study, it seems that vessels of all sizes were used for processing a wide range of commodities, since no correlation between the organic residue concentration and vessel rim diameter or rim type was found. Further investigation is required to elucidate why the aquatic biomarkers from the Typical/Late Comb Ware site were so much better preserved than those from other periods. Further investigations are also needed to determine whether there is any connection between the use of the vessel and the clay type or tempering. Further analyses of absorbed organic residues from vessels from inland Finland will also help identify more coherent trends regarding the food habits of Comb Ware people.

Finally, while absorbed organic residue analysis has been widely used to study animal husbandry and dairying, we have demonstrated here the usefulness of the approach for studying northern hunter-gatherer-fisher societies.

ACKNOWLEDGMENTS

We wish to thank Leena Koivisto and Satakunta Museum for providing the sherds from Pomarkku. The UK Natural Environment Research Council is thanked for mass spectrometry facilities (GR3/2951, GR3/3758 and FG6/36101). We also thank the reviewers for their valuable comments on the manuscript. The study was funded by the Academy of Finland (SA258294).

REFERENCES

Archival and unpublished sources

Bläuer, A. 2015. Osteologinen analyysi Ulvila Suoliston (TYA 112), Turku (Maaria) Jäkärlän (TYA 313, 336, 416, 427, 457, 559, 615) ja Kaarina (Piikkiö) Moision (TYA 369, 392, 444, 658) luuaineistoista. Research report, Department of Archaeology, University of Turku.

Fortelius, M. 1980a. Kokemäki Kraviojankangas 20584: Osteologinen analyysi. Research report, National Board of Antiquities, Helsinki.

Fortelius, M. 1980b. Pomarkku Myllytörmä 9560: Osteologinen analyysi. Research report, National Board of Antiquities, Helsinki.

Pääkkönen, M., Evershed, R.P. & Asplund, H. in preparation. Compound specific stable carbon isotope values of organisms from the Baltic Sea and Finland: Introducing new values for archaeological comparisons of northern Baltic region. Article manuscript.

Literature

Ackman, R.G. & Hooper, S.N. 1968. Examination of isoprenoid fatty acids as distinguishing characteristics of specific marine oils with particular reference to whale oils. *Comparative biochemistry and physiology* 24 (2): 549–65.

Alenius, T., Mökkönen, T. & Lahelma, A. 2013. Early farming in the northern boreal zone: Reassessing the history of land use in southeastern Finland through high-resolution pollen analysis. *Geoarchaeology* 28 (1): 1–24.

Alhonen, P. & Huurre, M. 1991. *Satakunnan historia I, 1: Satakunnan luonnon geologinen historia: Satakunnan kivikausi*. Pori: Satakuntaliitto.

Andrejev, O., Myrberg, K., Alenius, P. & Lundberg, P.A. 2004. Mean circulation and water exchange in the Gulf of Finland: A study based on three-dimensional modelling. *Boreal Environment Research* 9 (1): 1–16.

Asplund, H. 2006. Muinaisranta etääntyy Lounais-Suomessa: Geologian vai arkeologian ongelma. *Muinaistutkija* 2006 (4): 2–10.

Avigan, J. 1966. Pristanic acid (2,6,10,14-tetramethylpentadecanoic acid) and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid) content of human and animal tissues. *Biochimica et Biophysica Acta (BBA) – Lipids and Lipid Metabolism* 125 (3): 607–10.

Berstan, R., Stott, A.W., Minnitt, S., Bronk Ramsey, C., Hedges, R.E.M., Evershed, R.P. 2008. Direct dating of pottery from its organic residues: New precision using compound-specific carbon isotopes. *Antiquity* 82 (317): 702–13.

Bläuer, A. & Kantanen, J. 2013. Transition from hunting to animal husbandry in southern, western and eastern Finland: New dated osteological evidence. *Journal of Archaeological Science* 40 (4): 1646–66.

Bronk Ramsey, C. 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. *Radiocarbon* 37 (2): 425–30.

Bronk Ramsey, C. 2001. Development of the radiocarbon calibration program. *Radiocarbon* 43 (2A): 355–64.

Charters, S., Evershed, R.P., Goad, L.J., Leyden, A., Blinkhorn, P.W. & Denham, V. 1993. Quantification and distribution of lipid in archaeological ceramics: Implications for sampling potsherds for organic residue analysis and the classification of vessel use. *Archaeometry* 35 (2): 211–23.

Copley, M.S., Berstan, R., Dudd, S.N., Docherty, G., Mukherjee, A.J., Straker, V., Payne, S. & Evershed, R.P. 2003. Direct chemical evidence for widespread dairying in prehistoric Britain. *Proceedings of the National Academy of Sciences of the United States of America* 100 (4): 1524–9.

Copley, M.S., Hansel, F.A., Sadr, K. & Evershed, R.P. 2004. Organic residue evidence for the processing of marine animal products in pottery vessels from the pre-colonial archaeological site of Kasteelberg D east, South Africa. *South African Journal of Science* 100 (5–6): 279–83.

Correa-Ascencio, M. & Evershed, R.P. 2014. High throughput screening of organic residues in archaeological potsherds using direct acidified methanol extraction. *Analytical Methods* 6 (5): 1330–40.

Cramp, L. & Evershed, R.P. 2014. Reconstructing aquatic resource exploitation in human prehistory using lipid biomarkers and stable isotopes. In H. Holland & K. Turekian (eds.) *Treatise on Geochemistry*: 319–39. Amsterdam: Elsevier.

Cramp, L.J.E., Jones, J., Sheridan, A., Smyth, J., Whelton, H., Mulville, J., Sharples, N. & Evershed, R.P. 2014a. Immediate replacement of fishing with dairying by the earliest farmers of the northeast Atlantic archipelagos. *Proceedings of the Royal Society B: Biological Sciences* 281 (1780): 1–8.

Cramp, L.J.E., Evershed, R.P., Lavento, M., Halinen, P., Mannermaa, K., Oinonen, M., Kettunen, J., Perola, M., Onkamo, P. & Heyd, V. 2014b. Neolithic dairy farming at the extreme of agriculture in northern Europe. *Proceedings of the Royal Society B: Biological Sciences* 281 (1791): 1–9.

Dunne, J., Evershed, R.P., Salque, M., Cramp, L., Bruni, S., Ryan, K., Biagetti, S. & di Lernia, S. 2012. First dairying in green Saharan Africa in the fifth millennium BC. *Nature* 486 (7403): 390–4.

Edgren, T. 1966. *Jäkärlä-gruppen, en västfinsk kulturgrupp under yngre stenålder*. Suomen Muinaismuistoyhdistyksen Aikakauskirja 64.

Edgren, T. 1982. *Formgivning och funktion: En kamkeramisk studie*. Iskos 3.

Edgren, T. 1993. Den förhistoriska tiden. In T. Edgren & L. Törnblom (eds.) *Finlands historia 1:* 11–270. Esbo: Schildt.

Europaeus, A. 1926. Stenålderskeramik från kustboplatser i Finland. In C.A. Nordman (ed.) *Nordiska arkeologmötet i Helsingfors 1925*: 45–77. Suomen Muinaismuistoyhdistyksen Aikakauskirja 36 (1).

Evershed, R.P. 2008. Organic residue analysis in archaeology: The archaeological biomarker revolution. *Archaeometry* 50 (6): 895–924.

Evershed, R.P., Dudd, S.N., Copley, M.S., Berstan, R., Stott, A.W., Mottram, H., Buckley, S.A. & Crossman, Z. 2002. Chemistry of archaeological animal fats. *Accounts of Chemical Research* 35 (8): 660–8.

Evershed, R.P., Payne, S., Sherratt, A.G., Copley, M.S., Coolidge, J., Urem-Kotsu, D., Kotsakis, K., Özdoğan, M., Özdoğan, A.E., Nieuwenhuyse, O., Akkermans, P.M.M.G., Bailey, D., Radian-Romus, A., Campbell, S., Farid, S., Hodder, I., Yalman, N., Özbaşaran, M., Bıçakı, E., Garfinkel, Y., Levy, T. & Burton, M.M. 2008a. Earliest date for milk use in the Near East and southeastern Europe linked to cattle herding. *Nature* 455 (7212), 528–31.

Evershed, R.P., Copley, M.S., Dickson, L. & Hansel, F.A. 2008b. Experimental evidence for the processing of marine animal products and other commodities containing polyunsaturated fatty acids in pottery vessels. *Archaeometry* 50 (1): 101–13.

Gustafsson, B.G. & Westman, P. 2002. On the causes for salinity variations in the Baltic Sea during the last 8500 years. *Paleoceanography* 17 (3): 1–14.

Halinen, P. 2015. Kivikausi. In G. Haggrén, P. Halinen, M. Lavento, S. Raninen & A. Wessman *Muinaisuutemme jäljet: Suomen esi- ja varhaishistoria kivikaudesta keskiajalle:* 17–121. Helsinki: Gaudeamus.

Hansel, F.A. & Evershed, R.P. 2009. Formation of dihydroxy acids from Z-monounsaturated alkenoic acids and their use as biomarkers for the processing of marine commodities in archaeological pottery vessels. *Tetrahedron Letters* 50 (40): 5562–4.

Hansel, F.A., Copley, M.S., Madureira, L.A.S. & Evershed, R.P. 2004. Thermally produced ω-(*o*-alkylphenyl)alkanoic acids provide evidence for the processing of marine products in archaeological pottery vessels. *Tetrahedron Letters* 45 (14): 2999–3002.

Hansel, F.A., Bull, I.D. & Evershed, R.P. 2011. Gas chromatographic mass spectrometric detection of dihydroxy fatty acids preserved in the 'bound' phase of organic residues of archaeological pottery vessels. *Rapid Communications in Mass Spectrometry* 25 (13): 1893–8.

Heikkurinen-Montell, T. 1986. Kokemäen Kraviojankankaan savi-idolit. In T. Edgren (ed.) *Studia praehistorica Fennica C.F. Meinander septuagenario dedicata*: 31–6. Iskos 6.

Heron, C. Craig, O.E., Luquin, A., Steele, V.J., Thompson, A. & Piličiauskas, G. 2015. Cooking fish and drinking milk? Patterns in pottery use in the southeastern Baltic, 3300–2400 cal BC. *Journal of Archaeological Science* 63: 33–43.

Hopia, A., Reunanen, M. & Pesonen, P. 2003. GC-MS analysis of organic residues in the potsherd samples from Vantaa Maarinkunnas. *Finskt Museum* 102 (1995): 44–55.

Isaksson, S. 1997. Laboratory report concerning the lipid content and the fatty acid pattern of the organic material on four sherds from Otterböte, Kökar, Åland. In K. Gustavsson *Otterböte, New Light on a Bronze Age Site in the Baltic*: 169–76. Theses and Papers in Archaeology B: 4.

Janér, J.H. 1983. Arkeologisten näytteiden termoluminesenssiajoitus Suomessa. *Karhunhammas* 7: 1–8.

Jungner, H. & Sonninen, E. 1983. *Radiocarbon dates II.* Helsinki: University of Helsinki.

Jungner, H. & Sonninen, E. 1996. *Radiocarbon dates IV.* Helsinki: University of Helsinki.

Lahtinen, M. & Rowley-Conwy, P. 2013. Early farming in Finland: Was there cultivation before the Iron Age (500 BC)? *European Journal of Archaeology* 16 (4): 660–84.

Laukkanen, E. 1997. Kaivaukset Jäkärlässä vuosina 1981, -82 ja -85. In J. Kostet (ed.) *Arkeologisia tutkimuksia Varsinais-Suomessa 1980-luvulla*: 53–73. Turun maakuntamuseo monisteita 9.

Leppäranta, M. & Myrberg, K. 2009. *Physical Oceanography of the Baltic Sea*. Berlin: Springer.

Lougheed, B.C., Filipsson, H.L. & Snowball, I. 2013. Large spatial variations in coastal ^{14}C reservoir age: A case study from the Baltic Sea. *Climate of the Past* 9 (3): 1015–28.

Mannermaa, K. 2003. Birds in Finnish prehistory. *Fennoscandia Archaeologica* XX: 3–39.

Meinander, C.F. 1984. Kivikautemme väestöhistoria. In *Suomen väestön esihistorialliset juuret*: 21–48. Bidrag till kännedom av Finlands natur och folk 131.

Núñez, M. 1999. Role of food production in Stone Age Finland. In P. Fogelberg (ed.) *Pohjan poluilla: Suomalaisten juuret nykytutkimuksen mukaan*: 133–42. Bidrag till kännedom av Finlands natur och folk 153.

Olsson, M. & Isaksson, S. 2008. Molecular and isotopic traces of cooking and consumption of fish at an early medieval manor site in eastern middle Sweden. *Journal of Archaeological Science* 35 (3): 773–80.

Pesonen, P. & Leskinen, S. 2009. Pottery of the Stone Age hunter-gatherers in Finland. In P. Jordan & M. Zvelebil (eds.) *Ceramics Before Farming: The Dispersal of Pottery Among Prehistoric Eurasian Hunter-Gatherers:* 299–318. Walnut Creek: Left Coast Press.

Piezonka, H. 2012. Stone Age hunter-gatherer ceramics of north-eastern Europe: New insights into the dispersal of an essential innovation. *Documenta Praehistorica* 39: 22–51.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M. & van der Plicht, J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55 (4): 1869–87.

Roffet-Salque, M., Dunne, J., Altoft, D.T., Casanova, E., Cramp, L.J.E., Smyth, J., Whelton, H. & Evershed, R.P. in press. From the inside out: Upscaling organic residue analyses of archaeological ceramics. *Journal of Archaeological Science: Reports*.

Siiriäinen, A. 1981. On the cultural ecology of the Finnish Stone Age. *Suomen Museo* 87 (1980): 5–40.

Siiriäinen, A. 1982. Recent studies on the Stone Age economy in Finland. *Fennoscandia Antiqua* I: 17–26.

Sjörs, H., Jonsell, B. & Elven, R. 2004. Features of Nordic environment and vegetation. In B. Jonsell (ed.) *Flora Nordica: General volume:* 37–100. Stockholm: Bergius Foundation & Royal Swedish Academy of Sciences.

Skandfer, M. 2005. Early Northern Comb Ware in Finnmark: The concept of Säräisniemi 1 reconsidered. *Fennoscandia Archaeologica* XXII: 3–27.

Suominen, T., Tolvanen, H. & Kalliola, R. 2010. Surface layer salinity gradient and flow patterns in the archipelago coast of SW Finland, northern Baltic Sea. *Marine Environmental Research* 69 (4): 216–26.

Tallavaara, M., Pesonen, P. & Oinonen, M. 2010. Prehistoric population history in eastern Fennoscandia. *Journal of Archaeological Science* 37 (2): 251–60.

Tallavaara, M. & Seppä, H. 2012. Did the mid-Holocene environmental changes cause the boom and bust of hunter-gatherer population size in eastern Fennoscandia? *The Holocene* 22 (2): 215–25.

Torvinen, M. 2000. Säräisniemi 1 Ware. *Fennoscandia Archaeologica* XVII: 3–35.

Ukkonen, P. 1993. The post-glacial history of the Finnish mammalian fauna. *Annales Zoologici Fennici* 30 (4): 249–64.

Ukkonen, P. 1996. Osteological analysis of the refuse fauna in the Lake Saimaa area. In T. Kirkinen (ed.) *Environmental Studies in Eastern Finland: Reports of the Ancient Lake Saimaa Project*: 63–91. Helsinki Papers in Archaeology 8.

Ukkonen, P. 2001. *Shaped by the Ice Age: Reconstructing the History of Mammals in Finland during the Late Pleistocene and Early Holocene*. Helsinki: University of Helsinki.

Vormisto, T. 1985. Osteologisk bearbetning av benmaterial framgrävt av den arkeologiska institutionen vid Åbo Universitet 1975–1983. *Karhunhammas* 9: 135–77.

Zvelebil, M. 1981. *From Forager to Farmer in the Boreal Zone: Reconstructing Economic Patterns through Catchment Analysis in Prehistoric Finland*. BAR International Series 115.