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Lipid residue analysis on Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands) and its implications for human-animal interactions in relation to the Neolithisation process

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ABSTRACT

This paper focuses on the functional analysis of Swifterbant pottery (c. 5000–3800 cal BC) in the Lower Rhine-Meuse area (the Netherlands). It examines pottery use across the transition to agriculture and aims to assess temporal changes in human-animal relations during the 5th millennium BC in the Lower Rhine-Meuse area through lipid residue analysis. We conducted lipid residue analysis of 49 samples from four Swifterbant sites: Hardinxveld-Giessendam Polderweg, Hardinxveld-Giessendam De Bruin, Brandwijk-het Kerkhof, and Hazendonk. A combined approach using both GC-MS and GC-C-IRMS of residues absorbed into the ceramic was employed to identify their context. Their context was then compared to published faunal datasets to present the relative abundance of taxa detected in the lipid residues. Evidence of processing freshwater fish was found in all sites, presenting that it was a continuous and primary function of Swifterbant pottery in the Lower Rhine-Meuse area starting from its first appearance at c. 5000 cal BC till the end of 5th millennium BC regardless of vessel form, size, decoration or temper. The results of our analysis also present temporal changes in the exploitation of food resources from the early to the late 5th millennium BC. From the mid 5th millennium BC onwards, vessels were also used to process different ranges of foodstuffs such as terrestrial resources and dairy products. The identification of dairy residue is the first direct evidence so far from Swifterbant pottery. We tentatively explain these results as an indication of presence of different culinary practices that had developed through the 5th millennium in the Lower Rhine-Meuse area and that the use of Swifterbant pottery is a direct reflection of changing cultural preferences on food preparation and consumption.

1. Introduction

The term Neolithisation usually describes the transitional stages from the last hunter-gatherer communities to the first farming societies. The Neolithisation process, its timing and tempo, have traditionally been studied through observing changes in the subsistence economy, i.e. the inception of domesticated animal and plant remains, and through associated changes in material culture, such as pottery and stone tools. More recently, organic residue analysis has been used to examine both hunter-gatherer and early agricultural pottery use to look at economic change and offer new perspectives regarding culinary change and cooking practices at this important transition in prehistory. A clear pattern emerging from this growing body of research is the discrepancy

between the use of hunter-gatherer pottery, entirely from northern Europe, and early farmer pottery from southern, central and Atlantic Europe. Hunter-gatherer pots were frequently used for cooking both marine and freshwater aquatic resources, as observed in the earliest vessels to appear in mid-6th millennium cal BC in north-eastern Europe (i.e. Narva-type pottery in southeastern Baltic) (Oras et al., 2017; Robson et al., 2019) and 5th millennium cal BC in northern Europe (i.e. Ertebølle pottery (EBK) in southwest Baltic, although Ertebølle ceramics were also used for processing of terrestrial animal and plant resources; Courel et al., 2020; Craig, 2007, 2011; Heron et al., 2013; Papakosta, 2019; Philippsen and Meadows, 2014). This contrasts markedly with the early farming pottery outside of northern Europe where, with a few notable exceptions (Cramp et al., 2019), aquatic resources are virtually

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absent and ruminant meat and dairy products are frequently found (Guiry et al., 2016; Cramp et al., 2014, 2019; Smyth and Evershed, 2015; Debono-Spiteri et al., 2016; Cubas et al., 2019, 2020).

Although both hunter-gatherer pottery and early agricultural pottery have been studied in some detail (Craig et al., 2007; Dolukhanov et al., 2010; Povlsen, 2014; Křiška et al., 2017; Oras et al., 2017; Hommel, 2018; Bondetti et al., 2019; Courel et al., 2020; Cubas, 2019), there have been relatively fewer comparisons of pottery use across the transition to agriculture. Such comparisons are only possible in northern Europe, where the tradition of pottery use by hunter-gatherer communities was already established prior to the arrival of farming. In some regions, the arrival of agriculture is accompanied by marked changes in pottery forms and manufacturing techniques. Residue analysis of pottery sequences that span the arrival of agriculture, such as the EBK to Funnel Beaker (TRB) in southern Scandinavia (c. 4000 cal BC) (Craig et al., 2011; Isaksson and Hallgren, 2012; Sørensen and Karg, 2014; Sørensen, 2017) and 'subneolithic' to Corded Ware (CWC) in southeastern Baltic (c. 2900/2800 cal BC) (Piličiauskas et al., 2017; Cramp et al., 2014; Heron et al., 2015; Robson et al., 2019) show a mixture of traditional hunter-gatherer subsistence strategies, including exploitation of aquatic resources, and the early farming subsistence economies, often including dairy products. Unlike other early European farmers, in northern Europe aquatic products continued to be processed in pottery beyond the arrival of farming and perhaps were influenced by pre-existing indigenous culinary practices.

Here we examine pottery use across the transition to agriculture in the Lower Rhine-Meuse area. In this region pottery began to be produced at c. 5000 cal BC by hunter-gatherers, known as the Swifterbant tradition. At around 4500–4400 cal BC, there is some evidence that domesticated animals were incorporated into the Swifterbant economy followed by cereal cultivation at around 4300–4000 cal BC (Cappers and Raemaekers, 2008; Çakırlar et al., 2020). Unlike other regions of northern Europe, these introductions were not accompanied by major changes in pottery forms or manufacturing techniques. Nevertheless, it is not known whether the use of pottery changed in this region with the arrival of domesticated animals and plants. Previous organic residue analysis of pottery from three of the Swifterbant type sites (Swifterbant S2, S3, S4), dating to the end of the sequence (c. 4300–4000 cal BC),

show no evidence of domesticated animal products (Demirci et al., 2020) although domesticated cereals have been morphologically identified in the charred surface deposits of some vessels (Raemaekers et al., 2013). In this study, we examine a unique chronological transect of Swifterbant activity in the Lower Rhine-Meuse area. By comparing pottery use and faunal assemblages, we aimed to assess temporal changes in human-animal relations during the 5th millennium BC.

2. Archaeological sites

The lipid analysis was carried out on four Swifterbant sites in the Lower Rhine-Meuse area: Hardinxveld-Giessendam Polderweg (hereafter Polderweg), Hardinxveld-Giessendam De Bruin (hereafter De Bruin), Brandwijk-het Kerkhof (hereafter Brandwijk) and Hazendonk (Fig. 1). These sites provide the best sequence of Swifterbant pottery in the Lower Rhine-Meuse area, therefore allowing us to study the use of ceramics while across the transition to farming in the area. The Lower Rhine-Meuse area is a river delta in the Netherlands formed by the confluence of the Rhine and the Meuse rivers. At the end of the Late Pleistocene, the large riverbeds held relatively small rivers and the lack of vegetation cover allowed the sand at the surface to be transported by wind. As a result, a large number of river dunes were formed. From ca. 6000 BCE onwards, the sea level rise resulted in a rise of the groundwater in the area. In its turn, this caused sedimentation of peat and clay. As a result, the archaeological sites discussed here are located in a riverine landscape, where the river dunes provided sparse dry spots for occupation and exploitation (Louwe Kooijmans, 1974, 1993, 2003).

The occupation history of the four sites covers a period from c. 5500 to 3700 cal BC. All four sites were inhabited repeatedly. In this article we focus on the period c. 5000–3820 cal BC, from the oldest ceramics in Swifterbant style (Polderweg phase 2/ De Bruin phase 2; Raemaekers, 2011) to the end of the Swifterbant ceramic tradition (Brandwijk L60; Raemaekers, 1999: 52–53) in the area.

Overall, the pottery from the Lower Rhine-Meuse area sites fits the general description of Swifterbant pottery (Raemaekers: 30–31, 45–55, 63–65, 1999; Raemaekers, 2011; Raemaekers and de Roeve, 2010; Louwe Kooijmans, 2010). The pottery from the four sites is characterised by S-shaped, mostly open forms with slightly pointed or rounded bases.

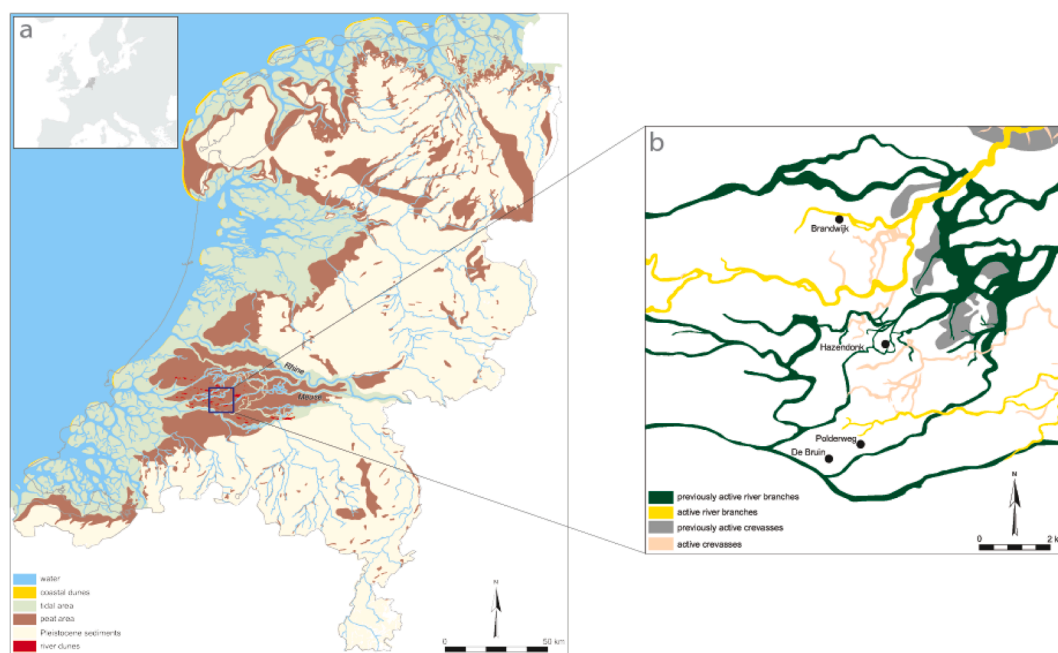


Fig. 1. Maps (a) showing the location of the Netherlands in relation to Europe and the location of the mentioned sites on a palaeogeographic map (3850 cal. BC) of the Netherlands (box), (b) showing the location of the four studied sites in relation to the various river branches. The white area consisted of marshes and lakes (Vos and de Vries, 2013; Vos, in prep.).

It was constructed using the coiling technique, with rim diameters varying from 15 to 40 cm (with the median diameter of 20 cm) and wall thicknesses from 5 to 12 mm (with the median thickness of 10 mm). In terms of fabric, all four sites produce extremely coarse pottery with mostly uneven surfaces. The surface treatment is rare and when present, varies between smoothing, smearing, roughening, and polishing. The most common inclusion for the Polderweg and De Bruin sherds is grit, although some grog and plant material appear as well. Almost all the sherds from Brandwijk and Hazendonk indicate plant material and/or grit as the main temper materials along with rare appearance of grog, sand, and mica. In terms of decoration, there is a temporal variation between the characteristics of the earlier Swifterbant pottery from Polderweg and De Bruin and later assemblages from Brandwijk and Hazendonk. In the earlier pottery assemblages, the decoration is uncommon and when present, it only appears as a series of spatula impressions on the top of the rim. In contrast, later assemblages present a higher distribution of vessels with wall and surface-covering decoration. Wall decorations vary between spatula impressions, thumb impressions, and hollow-circular impressions, while surface-covering decorations consist of either fingertip/nail or hollow spatula impressions. This temporal variation in decoration between earlier and later Swifterbant pottery is well illustrated in the sherds that have been subjected to lipid residue analysis (Supplementary Dataset-1).

All four sites used a broad range of subsistence strategies, exploiting a wide range of animal and plant taxa, including large and small game, terrestrial and aquatic, fowl and fish, nuts and berries. This wide scope remained consistent throughout the period under study (Brinkhuizen, 1979; Zeiler, 1997; Raemaekers, 1999; Louwe Kooijmans, 2003, 2001a, 2001b, 2007; Oversteegen et al., 2001). Deer (Cervidae), *Sus* sp., otter (*Lutra lutra*) and beaver (*Castor fiber*) are the most abundant mammals recovered at all sites. Otter and beaver were hunted in large numbers, and their meat as well as fur were exploited (Zeiler, 1997). It is difficult to assess the role of domestic animals in subsistence during this period (Rowley-Conwy, 2013; Çakırlar et al., 2020; Dusseldorp and Amkreutz, 2020). Analysis of mitochondrial aDNA of four *Sus* teeth of unclear phenotype from the late 5th millennium BC Swifterbant site S4 shows the prevalence of European maternal lineages in *Sus* there (Krause-Kyora, 2011; Kranenburg and Prummel, 2020). However, since intermixing between local wild boar and domestic pigs with origins in the Near East was very common (Frantz et al., 2019), information about maternal lineages alone adds little to the understanding of the nature of pig/boar use at this juncture. *Bos* sp. first appear in the younger phases of De Bruin, and always remain in low numbers (Çakırlar et al., 2020). Although small sample sizes do not allow reconstructing population-wide patterns in morphology and mortality, the absence of aurochs (*Bos primigenius*) in Polderweg and De Bruin phase 1, and the size and age-at-death variation represented by *Bos* specimens may suggest the presence of domesticated cattle herds possibly in De Bruin phase 3 and Brandwijk, and more probably in Hazendonk.

The most secure indication for the presence of domesticated animals in the archaeological record of the Lower Rhine-Meuse area in the Swifterbant period is the few remains of sheep or goat bones at De Bruin and Brandwijk. The earliest directly dated domesticated animal specimen in the region comes from De Bruin and is dated to 4520–4356 cal BC (Çakırlar et al., 2020: Table 13.5). Since sheep and goat are not native to Europe, it is certain that these animals must have been introduced to the area from regions to the south or east where farming was already established at this time. Albeit osteomorphological analyses suggest that some remains might belong to the same individual, decreasing the total number of identified sheep/goat specimens while increasing the uncertainties in their interpretation (Çakırlar et al., 2020). Future studies amalgamating zooarchaeology with high-resolution radiocarbon, stable isotope, and palaeogenomic analyses is needed to resolve this issue.

Given the ambiguity in the identification of wild vs. domesticated suids and bovids, '*Sus* sp.' '*Bos* sp.' are referred to hitherto. This

classification also reflects the specificity that can be achieved by lipid residue analysis, which is unable to distinguish wild from domesticated ruminant and porcine fats.

From the high frequency of fish bone remains, it is clear that fishing was a key activity at all sites. All sites provide clear evidence for freshwater (i.e. pike [*Esox lucius*], perch [*Perca fluviatilis*], catfish [*Silurus glanis*], carp family (Cyprinidae)), anadromous (i.e. sturgeon [*Acipenser sturio*], eel [*Anguilla anguilla*], salmon/sea trout [*Salmo salar* cf. *trutta*], allis shad [*Alosa alosa* L.]) and occasional appearance of marine (mullet family (Mugilidae)) species (Brinkhuizen, 1979; Zeiler, 1997). Bird bones are relatively less common compared to mammal and fish remains in all four sites and mainly comprise duck (Anatidae), especially mallard (*Anas platyrhynchos*).

The archaeobotanical remains indicate that gathering remained an important subsistence strategy throughout the 5th millennium BC. All sites show evidence of numerous remains of wild plant species including acorn, hazelnut, water caltrop, wild apple and various berries. Archaeobotanical analyses also present the introduction of possible small-scale crop cultivation in the Lower Rhine-Meuse area. Brandwijk phases L50 and L60 and Hazendonk phase 1 yielded emmer wheat (*Triticum turgidum* ssp. *dicoccum*) and naked barley (*Hordeum vulgare* var. *nudum*) from 4220 to 3820 cal BC and 4020–3960 cal BC onwards respectively (Fig. 6) (Bakels, 1981; Out, 2008, 2009). Moreover, the study of anthropogenic influence on the vegetation indicates a restricted clearance of woodland (i.e. *Tilia* sp., *Quercus* sp. and *Alnus glutinosa*) and development of open patches at Brandwijk and Hazendonk. This may imply small-scale local cultivation at these sites (Out, 2009). The same cereals were found at other sites of the Swifterbant culture (Out, 2009; Schepers and Bottema-Mac Gillavry, 2020), while several cultivated field were recovered at the sites at Swifterbant (Huisman et al., 2009; Huisman and Raemaekers, 2014; Raemaekers and De Roever, 2020), strengthening the interpretation of local cultivation instead of imported crops. We consider the period of c. 4300–4000 cal BC the introduction date of cereal cultivation in the Swifterbant culture.

All four sites are considered to be seasonally occupied, where the function did not change over time, but occasional year-round occupation cannot be excluded either (Louwe Kooijmans, 1993, 2001a, 2001b; Raemaekers: 59–61, 1999).

3. Material and methods

3.1. Sampling strategy

A total of 49 samples (Polderweg, n = 9; De Bruin, n = 17; Brandwijk, n = 14; and Hazendonk, n = 9) were subjected to lipid residue analysis, all representing individual vessels. Of all samples, 17 (4 from Polderweg, 3 from De Bruin, and 10 from Brandwijk) have traces of carbonised remains (foodcrust) on interior and/or exterior surfaces, indicating that they had been used for cooking. Samples were selected from the Swifterbant pottery phases of each site (see Table 1). Pottery from all four Swifterbant sites, Polderweg, De Bruin, Brandwijk, and Hazendonk,

Table 1

Dates and archaeological phases associated with the samples from the four sites in the Lower Rhine-Meuse area (in chronological order).

Site	Phase/ Layer	Number of vessels sampled	Age /cal B. C.	Reference
De Bruin	Phase 2	2	5100–4800	Mol and Louve Kooijmans, 2001
Polderweg	Phase 2	9	5050–4950	Louwe Kooijmans and Mol, 2001
De Bruin	Phase 3	15	4700–4450	Mol and Louve Kooijmans, 2001
Brandwijk	L50	15	4220–3940	Verbruggen, 1992
Hazendonk	1	9	4020–3960	Verbruggen, 1992
Brandwijk	L60	1	3940–3820	Verbruggen, 1992

were highly fragmented courseware. Therefore, the sample size of each site is constrained to individual vessel fragments that provided different typological and morphological features and are large enough to be sampled. When available, rim fragments were preferentially selected as experimental studies suggest that lipids tend to accumulate on the rim due to the boiling of food products in the ceramic vessels (Charters et al., 1993). However, base fragments and decorated body sherds were also analysed as they are also diagnostic fragments providing information on the typology and the morphology of the pot. During the process of selecting samples, the form, size, decoration, rim diameter, wall thickness, and temper were recorded (Supplementary Dataset-1).

3.2. Lipid residue extraction

Samples were drilled from the interior surface of each vessel and were subjected to lipid extraction by established standard one step acidified methanol protocol (Craig et al., 2013; Papakosta et al., 2015). All extractions were analysed by Gas Chromatography-Mass Spectrometry (GC-MS), using different columns and modes for identification of different biomarkers (i.e. aquatic biomarkers) (Hansel et al., 2004; Regert, 2011; Cramp and Evershed, 2014; Lucquin et al., 2018), and Gas Chromatography-Combustion-Isotope Ratio Mass Spectrometry (GC-C-IRMS) for the measurement of compound-specific carbon stable isotopic ratios of the two most abundant fatty acids; $C_{16:0}$ and $C_{18:0}$, according to previously described protocols (Craig et al., 2012). To assess the corresponding zooarchaeological evidence, published faunal datasets were re-evaluated to quantify the relative abundance of taxa detected in the lipid residues and the taxonomic identification of relevant specimens were checked. The zooarchaeological data were further assessed to reconstruct patterns in body part representation, fragmentation, and mortality, but either sample size or data inaccessibility due to deficiencies in records and their metadata, or both hampered data re-use. Further detailed information on the methods can be found in the Supplementary Materials-Methods.

4. Results and interpretations

4.1. Results of molecular analysis (GC-MS)

All samples ($n = 49$) yielded sufficient quantities of lipids required for interpretation ($>5 \mu\text{g g}^{-1}$) with a mean value of $122 \mu\text{g g}^{-1}$ (ranging from $8 \mu\text{g g}^{-1}$ to $1,343 \mu\text{g g}^{-1}$) (Supplementary Dataset-1).

In general, the lipid profiles obtained from each sample contained saturated fatty acids, ranging from $C_{10:0}$ to $C_{28:0}$, dominated by mid-chain saturated acids, palmitic acid ($C_{16:0}$) and stearic acid ($C_{18:0}$), respectively. The $C_{16:0}$ and $C_{18:0}$ ratios (P/S ratios) of all the samples are listed in the Supplementary Dataset-1. Thirty-four of all the samples yielded unsaturated fatty acids from $C_{15:1}$ to $C_{24:1}$, dominated by oleic acid ($C_{18:1}$). Branched fatty acids ($C_{12} - C_{25}$) were also identified in 43 of all the samples. Dicarboxylic acids are present in 28 samples (58%), all with C_9 (azelaic acid), of which two also have C_{10} . A total of 16 samples yielded cholesterol and its derivatives, indicating the presence of animal fats.

In addition, biomarkers for aquatic products were identified in 31 of all 49 samples (Supplementary Dataset-1). Co-occurrence of ω -(*o*-alkylphenyl) alkanolic acids (APAAs), with carbon atoms ranging from 18 to 22, and isoprenoid fatty acids which are TMTD (4,8,12-trimethyltridecanoic acid), pristanic acid (2,6,10,14-tetramethylpentadecanoic acid), and phytanic acid (3,7,11,15-tetramethylhexadecanoic acid) is accepted as the established criteria for identifying aquatic lipids in the ancient pottery (Evershed et al., 2008a; Hansel et al., 2004; Craig et al., 2007; Cramp and Evershed, 2014; Heron et al., 2015). As APAAs are formed by heating ($\geq 200^\circ$, $>5\text{h}$; Bondetti et al., 2020) of mono and polyunsaturated fatty acids, their presence shows that these pots were used for cooking.

While TMTD is considered more of a characteristic of aquatic oils,

pristanic and phytanic acids are found in both aquatic and ruminant resources (Ackman and Hooper, 1968; Heron and Craig, 2015). To investigate the origin of phytanic acid found in the samples, we study the ratio of the two diastereomers of phytanic acid (3S,7R,11R,15-phytanic acid (SRR) and 3R,7R,11R,15-phytanic acid (RRR)) as the SRR isomer tends to predominate in aquatic oils ($>75.5\%$ relative abundance) compared to ruminant fats (Lucquin et al., 2016). In total, 61% of the samples with phytanic acid meet this criterion. For the remaining samples, the SRR/RRR ratio is either not available or falls within both the aquatic and ruminant range. Further 16 samples yielded partial aquatic biomarkers, containing C_{18} APAA and at least one isoprenoid acid which is also an indication of possible process of aquatic resources in these vessels (Evershed et al., 2008a; Heron and Craig, 2015), although not definitive.

Although the presence of C_{20} APAA has been widely used to identify aquatic products in ancient pottery (Hansel et al., 2004; Cramp and Evershed, 2014), an experimental study undertaken by Bondetti et al. (2020) demonstrates that these compounds can also be formed by heating mammalian tissues. Nevertheless, this study found that the C_{20} APAAs in heated aquatic products are at much greater relative abundance compared to C_{18} components whereas the APAA C_{20}/C_{18} ratio was substantially lower in mammalian tissues. Based on their results, Bondetti et al. assign an APAA C_{20}/C_{18} ratio of 0.06 as the lower limit for the identification of aquatic products. Here, all four sites provide a significantly large number of beaver bone remains (Fig. 6) hence beaver may have been a commodity processed in pottery, particularly for rendering the fatty tail meat (Coles, 2006). To investigate, we measured the APAA C_{20}/C_{18} in 12 Swifterbant vessels and found that in all cases the values were above 0.06 (varying between 0.16 and 0.76; Supplementary Dataset-1) and therefore corresponding to reference fish samples rather than the mammalian dataset that included beaver (Bondetti et al., 2020). For the remaining samples, the APAA C_{20}/C_{18} ratio was not possible to measure accurately.

As further evidence for distinguishing aquatic products from beaver as well as dairy products, we also looked at the branched fatty acids ($C_{15\text{br}}$ and $C_{17\text{br}}$) in samples with fully aquatic biomarkers ($n = 31$). Iso-branched fatty acids predominant in fish oils (Hauff and Vetter, 2010; Garnier et al., 2018), while anteiso- branched fatty acids are more predominant in beaver fat (Käkelä et al., 1996) and also in dairy products (Hauff and Vetter, 2010); the iso- branched fatty acids account for $59 \pm 16\%$ of the C_{15} and $59 \pm 5\%$ of the C_{17} branched fatty acids in fish oils, $38 \pm 6\%$ of the C_{15} and $34 \pm 2\%$ of the C_{17} branched fatty acids in dairy products and $19 \pm 4\%$ of the C_{15} and $35 \pm 12\%$ of the C_{17} branched fatty acids in beaver adipose and flesh tissue fats, the latter from Estonia, Russia and Canada (*Castor fiber* and *Castor canadensis*, $n = 10$; Supplementary Dataset-3). Of the samples from the Lower Rhine-Meuse Swifterbant samples with fully aquatic biomarkers ($n = 31$), $61 \pm 0.8\%$ of the C_{15} and $53 \pm 10\%$ of the C_{17} branched fatty acids (Supplementary Dataset-1) are present as iso-fatty acids and therefore are comparable with fish oils rather than beaver fats or dairy products. It is important to note here that the potential effect of the burial environment on this ratio is not known and needs to be tested in further studies.

Finally, none of the samples yielded plant derived lipids (e.g. phytosterols) (Supplementary Dataset-1). It is important to mention here that these results are based on acid extraction and none of the samples have been subjected to solvent extraction to identify cereal derived lipids. Interestingly, the clear presence of carbonized macro remains of numerous food plants found at all four sites suggest that they were processed as part of the food preparation (Out, 2009). In addition, archaeobotanical studies at Brandwijk and Hazendonk indicate the presence of micro remains (i.e. pollen) of crop plants in high amounts (Out, 2009). As naked barley and emmer wheat release the highest amount of pollen during threshing, its presence clearly indicates processing of cereal products at these two sites (Out, 2008, 2009). Although this can be explained by the application of other techniques not requiring ceramics to process food plants, we know that food plants have

a low lipid content and may be masked by other animal fats processed in pots (Colonese et al., 2017; Hammann and Cramp, 2018). This, therefore, makes it very difficult to identify the presence of food plants through lipid residue analysis. We also know that the scanning electron microscope (SEM) analysis on the carbonized surface deposits (food-crust) collected from another Swifterbant site, Swifterbant S3, has shown that the pots were also used for processing plant materials (Raemaekers et al., 2013). Given that, the absence of plant biomarkers in Swifterbant pottery through lipid residue analysis should be approached cautiously.

4.2. Isotopic identification of individual fatty acids (GC-C-IRMS)

In order to provide more information on the origin of the lipid residues, the carbon stable isotope values of palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids were analysed by GC-C-IRMS. Analyses included 48 samples which yielded sufficient fatty acids ($>5 \mu\text{g g}^{-1}$). The data from the samples are listed in and Supplementary Dataset-1. They are plotted in Fig. 3 against the reference ranges of authentic modern animal fats collected from the western Baltic, except for modern beaver fat which was collected from eastern Baltic.

Overall, the majority of the $\delta^{13}\text{C}$ values of $C_{16:0}$ and $C_{18:0}$ fatty acids

from all four sites are consistent with freshwater organisms (Fig. 3). Of 31 samples with fully aquatic biomarkers, 27 plots in this range. Although beaver also plots within the freshwater range (Fig. 3), both APAA C_{20}/C_{18} ratios and iso to anteiso ratio of C_{15} and C_{17} branched fatty acids refute the possible presence of beaver in these pots. Therefore, there is compelling evidence that these vessels were regularly used for processing freshwater fish.

Three samples from Brandwijk and five samples from Hazendonk plot within the range of modern porcine and marine fats (Fig. 3c and d). *Sus* sp. is abundant at Brandwijk (30% of all identified mammal fragments in L50, Number of Fragments (NF) = 73; 22% of all identified mammal fragments in L60, NF = 99; See Supplementary Dataset-2). *Sus* sp. is also present at Hazendonk (10% of all identified mammal fragments in Hazendonk 1/2; NF = 167, and 11% of all identified mammals in Hazendonk 3; NF = 490) (Zeiler, 1997; Çakırlar et al., 2019). While marine taxa are virtually absent from the zooarchaeological record of both sites, anadromous fish species are present in Brandwijk and Hazendonk. The species include sturgeon, salmon/sea trout, and allis shad (the latter only in Hazendonk) (Brinkhuizen, 1979). It is important to mention here that sturgeon represents a relatively large portion (3.1%, NF = 991 in L50; 3.8%, NF = 415 in L60) of the total fish bone remains at Brandwijk (Raemaekers, 1999: Table 3.27). Although it is

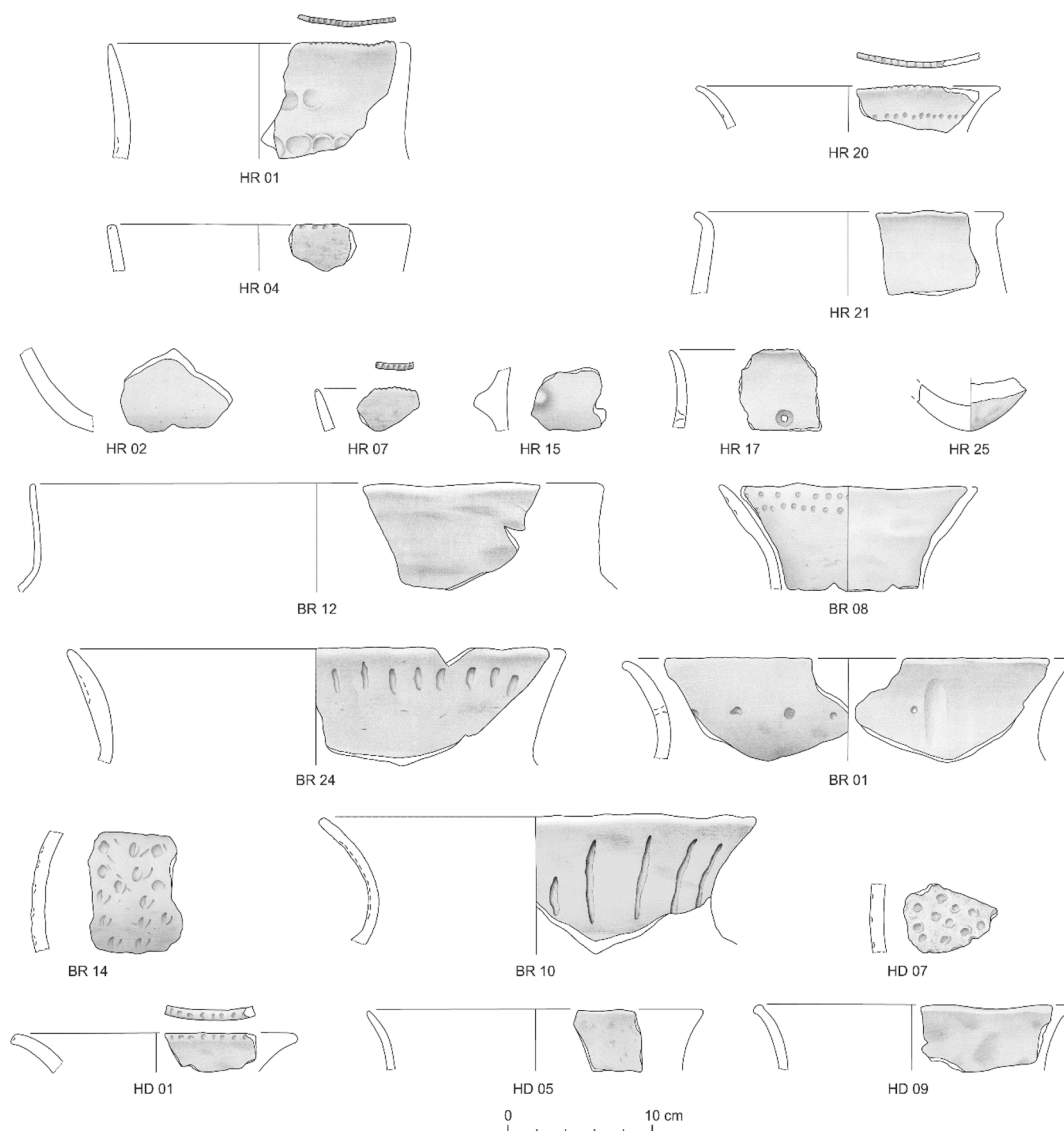


Fig. 2. Illustrations of selected sherds from Polderweg (HR01-HR07), De Bruin (HR15-HR25), Brandwijk (BR) and Hazendonk (HD).

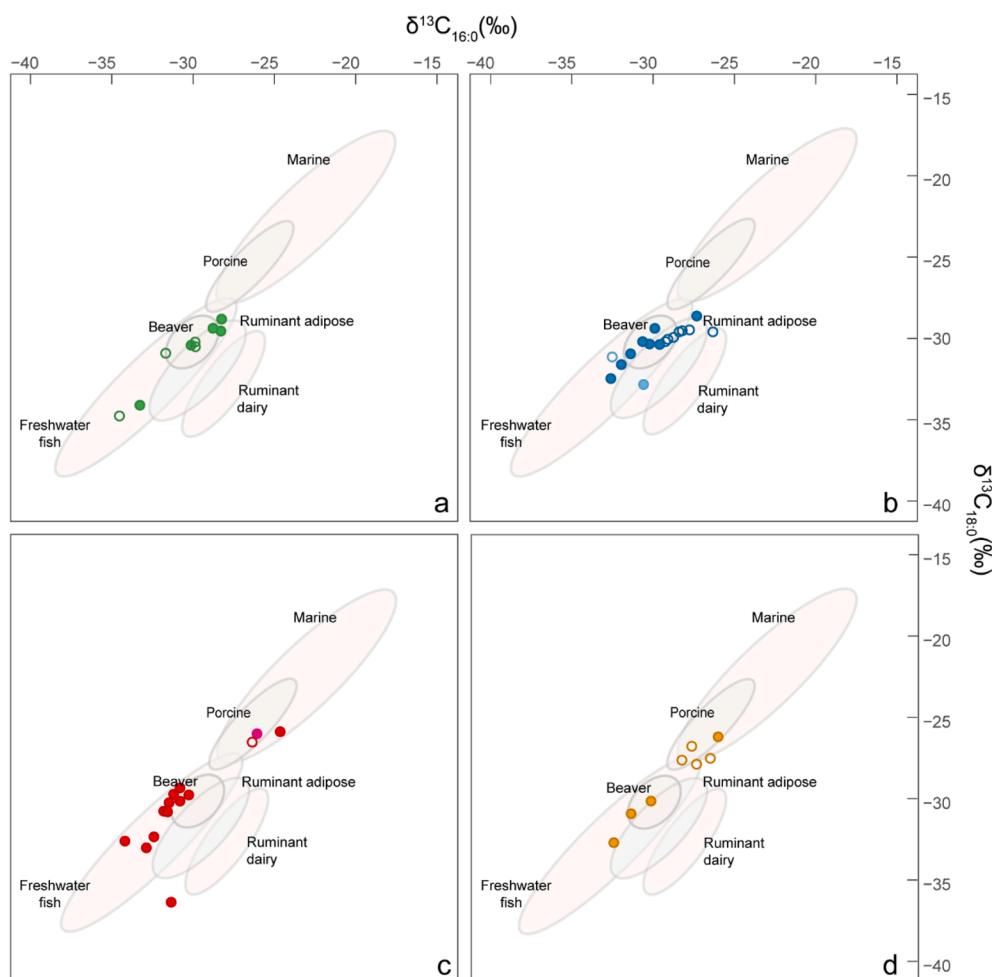


Fig. 3. GC-C-IRMS results showing isotopic values of $C_{16:0}$ and $C_{18:0}$ fatty acids of (a) Polderweg phase 2 ($n = 9$) in green, (b) De Bruin phase 3 ($n = 15$) in blue and phase 2 ($n = 2$) in light blue, (c) Brandwijk L50 ($n = 13$) in red and L60 ($n = 1$) in pink, and (d) Hazendonk 1 ($n = 9$) in orange. Samples with the full set of aquatic biomarkers are shown by filled circles. 95% confidence ellipses indicate areas of authentic reference values for each group of origins from western Baltic, and for beaver from eastern Baltic.

difficult to know the exact isotope values of sturgeon without its collagen analysis, the possibility of it being processed in the vessels cannot be ruled out for this site. Based on the faunal remains and on the fact that one of the three Brandwijk samples and all five of Hazendonk samples contain partial aquatic biomarkers (Supplementary Dataset-1), we can conclude that these samples contain a mixture of aquatic (mainly freshwater) and porcine derived lipids.

In Fig. 4, the $\delta^{13}C$ values of the $C_{16:0}$ acid are also plotted against the difference between the two major fatty acids ($\Delta^{13}C = \delta^{13}C_{18:0} - \delta^{13}C_{16:0}$) (Supplementary Dataset-1). This enables us to differentiate ruminant adipose, non-ruminant, and dairy fats (Dudd, 1999; Craig et al., 2012, 2013; Cramp and Evershed, 2014; Taché and Craig, 2015). $\Delta^{13}C$ values lower than -1‰ are typical of ruminant fats (Dudd et al., 1998; Evershed et al., 2002; Copley et al., 2003; Craig et al., 2012). Seven samples from De Bruin plotted in the ruminant adipose fat range and another two in between non-ruminant and ruminant adipose fat ranges (Fig. 4b). Faunal material from De Bruin shows the presence of *Bos* sp. and sheep/goat (0.2% and 0.1% of identified mammal bones in Phase 2, NF = 1728; 4% and 1.8% in Phase 3, NF = 591, respectively) as well as red deer remains ($\sim 3.2\%$ of identified mammal bones in Phase 2, NF = 1728; and in Phase 3, NF = 591) (Fig. 6B; Supplementary Dataset-2) (Louwe Kooijmans, 2007; Oversteegen et al., 2001; Amkreutz, 2013; Çakırlar et al., 2019, 2020). The presence of a series of cut and chop marks on these remains also indicates that they were processed for consumption (Clason, 1978). As three of these vessels have fully aquatic biomarkers and four of the remaining five are partially aquatic, we conclude that the residue is derived from a mixture of freshwater and ruminant fats.

One sample from Polderweg is in the ruminant adipose fat range (Fig. 4a). In terms of the presence of ruminant animals at Polderweg, faunal records indicate a total absence of domesticated animals and red deer covers only 0.8% of identified mammal bones (in Phase 2, excluding antlers, NF = 233) (Fig. 6B; Supplementary Dataset-2) (Van Wijngaarden-Bakker et al., 2001; Çakırlar et al., 2019). In addition, this sample has fully aquatic biomarkers. However, it is known that even a minor contribution of ruminant fat can be detected given there is a strong bias against aquatic oils when mixed with ruminant fats due to the difference in fatty acid concentration between these products (Cramp et al., 2019). Based on these, we conclude that this residue may also be a possible mixture of lipids derived from aquatic and ruminant fats.

Finally, one sample from Brandwijk L50 (BR08) clearly plots below the limit for wild ruminant carcass fats (-4.3‰ ; Craig et al., 2012) (Fig. 4c), meeting widely accepted criteria for ruminant dairy fats (Copley et al., 2003; Evershed et al., 2008b; Debono-Spiteri et al., 2016). As this sample (BR08) has fully aquatic biomarkers, this residue likely contains a mixture of lipids derived from both aquatic and dairy sources. Although no other sample plot in the dairy range, it is important to mention that low quantities for dairy fats would not be detected using these criteria when mixed with relatively high quantities of non-ruminant lipids (including aquatic) (Debono-Spiteri et al., 2016; Cramp et al., 2019).

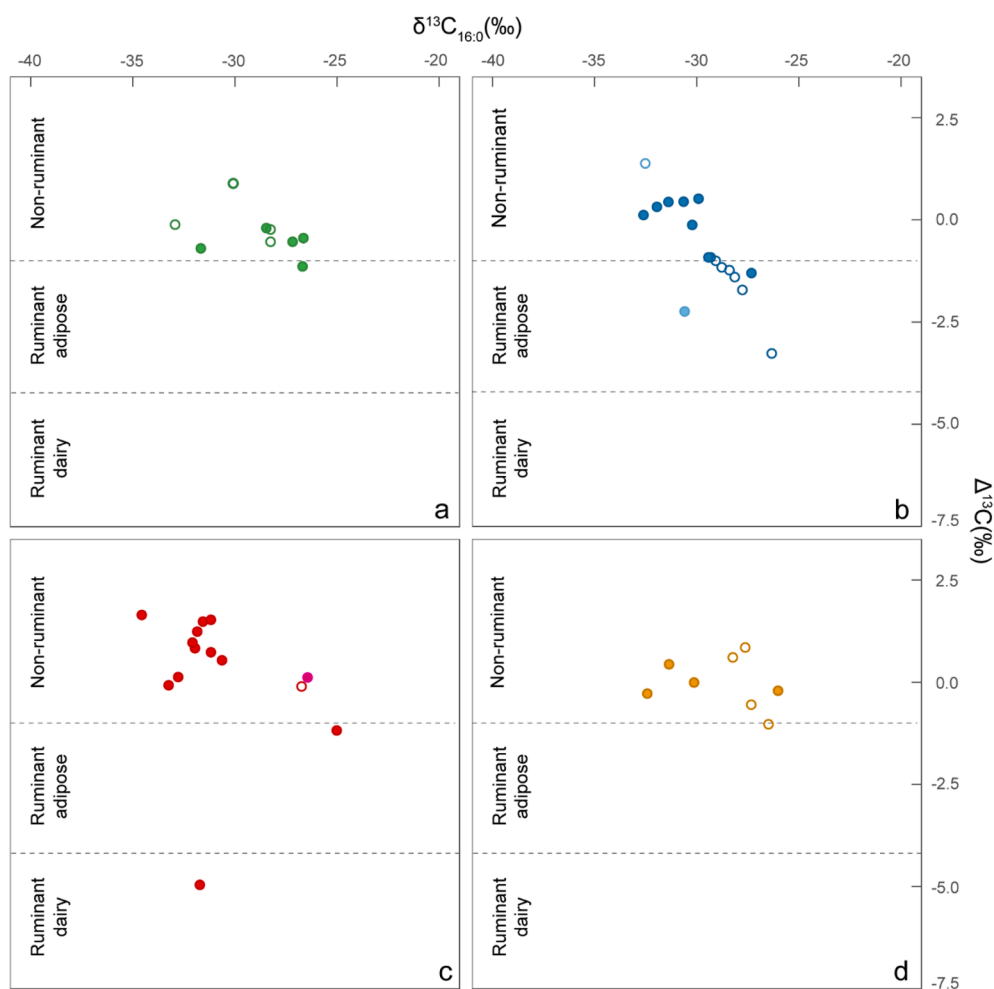


Fig. 4. $\Delta^{13}C$ ($\delta^{13}C_{18:0} - \delta^{13}C_{16:0}$ values) against $\delta^{13}C_{16:0}$ values of Swifterbant pottery from only ceramic matrices. (a) Polderweg phase 2 (n = 9) in green, (b) De Bruin phase 3 (n = 15) in blue and phase 2 (n = 2) in light blue, (c) Brandwijk L50 (n = 13) in red and L60 (n = 1) in pink, and (d) Hazendonk 1 (n = 9) in orange. Samples with the full set of aquatic biomarkers are shown by filled circles. Dotted lines indicate designated areas of authentic modern reference values for each group of origins from Western Baltic.

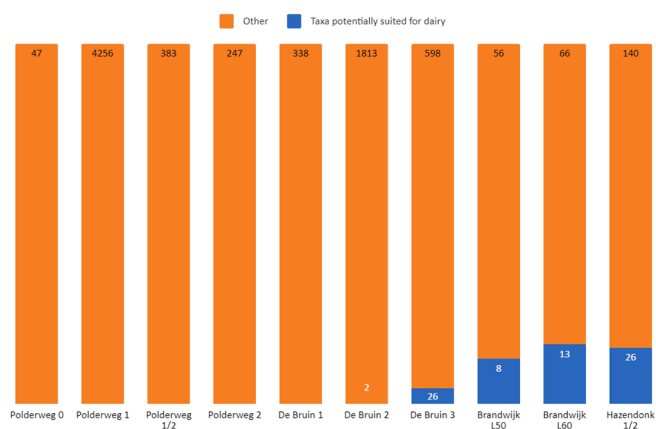


Fig. 5. The proportion of potentially dairy producing species to other food mammals in Number of Fragments (=NF) identified in the different phases of Polderweg, De Bruin, Brandwijk and Hazendonk. Data labels = NF.

5. Discussion

5.1. Functional continuity of the Swifterbant pottery for freshwater fish processing

Our research provides new insight into the function of Swifterbant pottery, starting from its first appearance at c. 5000 cal BC, throughout the 5th millennium in the Lower Rhine-Meuse area. The molecular and

isotopic evidence show that this pottery was heavily used for processing freshwater resources regardless of vessel form, size, decoration (Fig. 2) or temper (Supplementary Dataset-1). Processing of freshwater resources seems to have been the primary function of Swifterbant pottery, for over 1000 years, despite the introduction of domesticated animals and plants.

Similarly, previous studies have shown that aquatic resources were extensively processed in hunter-gatherer ceramics throughout northern Europe (Craig et al., 2007; Heron et al., 2015; Oras et al., 2017), although in some cases they were mixed with terrestrial products and foodplants (i.e. Ertebølle pottery; Courel et al., 2020; Papakosta, 2019). This practice continued beyond the arrival of agriculture. Recent residue analysis of vessels from three other Swifterbant sites, Swifterbant S2, S3 and S4 (ca. 4300–4000 cal BC) (Demirci et al., 2020) also shows a dominance of freshwater fish.

5.2. Economic importance of pig

Unlike Polderweg and De Bruin, Brandwijk and Hazendonk yielded evidence for porcine fats in the vessels. The vessels with porcine fats did not show any specific morphological or technological differences compared to the pottery assemblages as a whole. We conclude that the processing of *Sus* sp. changed from Brandwijk L50 onward. Although it is difficult to assess the importance of the *Sus* sp. in subsistence through lipid residue analysis, the combination of our results and the zooarchaeological record provides some clues about what might lie behind this change. Suid remains are abundant in the zooarchaeological assemblages of the Lower Rhine-Meuse area dating to the 6th millennium BC

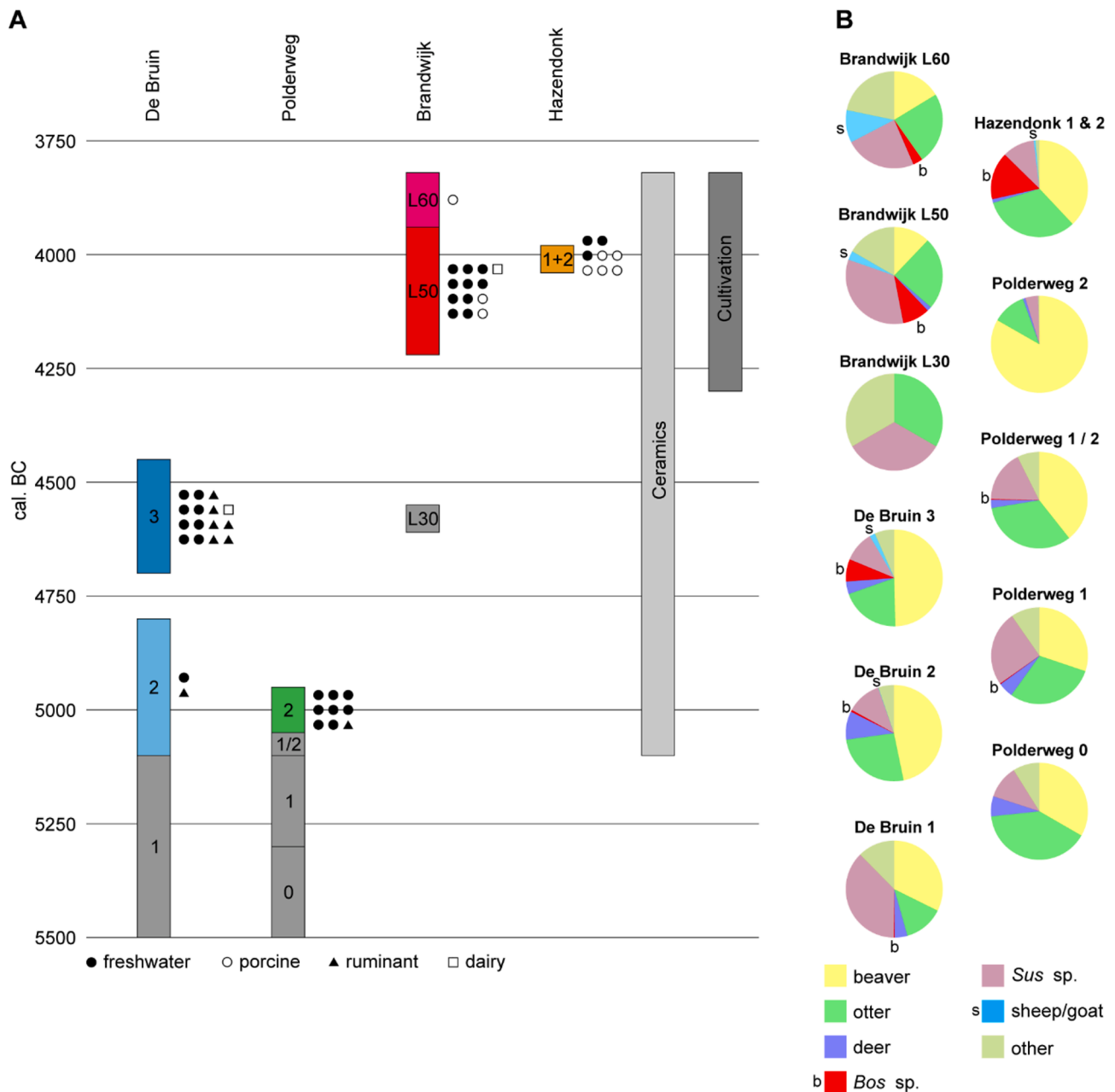


Fig. 6. (A) Figure showing dating, arrival pottery and starting date of cultivation of four Lower Rhine-Meuse area sites discussed in this study. Polderweg phase 2 (n = 9) in green, De Bruin phase 2 (n = 2) in light blue and phase 3 (n = 15) in blue, Brandwijk L50 (n = 13) in red and L60 (n = 1) in pink, and Hazendonk 1 (n = 9) in orange. (B) Pie charts showing the distribution of identified (wild and/or domestic) mammal bone remains (=NF). Based on the references listed in Supplementary Dataset-2.

and they remain so in the 5th millennium BC (Fig. 6B). A recent study on the bone remains show that small-sized *Sus* sp., possibly representing domesticated pigs, are absent in Polderweg and De Bruin, while they appear in Brandwijk L60 (Çakırlar et al., 2020). The pig population at Brandwijk seems to have been culled at younger ages than the individuals exploited in Polderweg and De Bruin. Size and age-at-death data suggest a change in pig management, possibly with the appearance of smaller, domesticated pigs interbreeding with wild boar.

This change in pig management seems to correlate to the presence of porcine fat in the Brandwijk and Hazendonk vessels. Interestingly, the *Sus* sp. is represented almost exclusively by cranial and distal extremity elements (i.e. head and feet) in Brandwijk. While this pattern of body part representation is markedly different from Polderweg, De Bruin, and Hazendonk, the Brandwijk sample is relatively small (NF = 22 in both

L50 and L60) and it is difficult to pinpoint what the differential body part representations mean. One possibility is that the Brandwijk inhabitants received only parts of the carcass, another is that the inhabitants of Brandwijk processed pork off site, with a cooking tradition that favoured heads and feet. Reported data allow us to calculate average *Sus* sp. fragment weight per assemblage (see Supplementary Dataset-2: Table 1), which shows a decreasing trend from Polderweg to De Bruin. Although bone weight can be influenced by post-depositional factors such as leaching and burning, and excavation methods such as sieving, it is considered a good index of carcass processing techniques because it can decrease when pot-sizing and grease extraction become more common in culinary practices (Gifford-Gonzalez, 2018). The reduced weight of *Sus* sp. fragments in the younger phases of De Bruin, Brandwijk, and Hazendonk may be associated with a new practice of

cooking pork in pots.

5.3. Evidence of ruminant fats

Lipid residue analysis indicates a changing approach to processing ruminant resources in the pots from these four Swifterbant sites. It is only in De Bruin phase 3 that we see clear evidence of processing ruminant resources in the pots. While Polderweg has only one sample yielding ruminant fats, ruminant carcass fats are completely absent in Brandwijk and Hazendonk samples. The pots with ruminant fats do not deviate from the other pots in terms of their morphological or technological features. Therefore, processing ruminant resources in the pots may be explained with specific local cultural preferences in culinary practices and/or changing human-animal relations rather than any gross changes in subsistence strategies.

Zooarchaeological records show the presence of ruminant in all four sites (Supplementary Dataset-2) and various species of deer, *Bos* sp. and sheep/goat could be the source of these ruminant fats in the pots. There is one sample from Polderweg that yielded $\Delta^{13}\text{C}$ values matching to ruminant adipose (see Fig. 4a, Supplementary Dataset-1). As domesticated ruminants seem absent from Polderweg, it is most likely that the vessel with adipose fat is derived from wild ruminants, such as deer or aurochs. If that is the case, although the combination of our results and the faunal data suggest that the samples from De Bruin with ruminant fats may indicate processing domesticated animals, processing wild ruminant food resources, possibly deer, in these pots is equally possible.

5.4. Dairy products in the Swifterbant pottery

Dairy is readily identifiable in prehistoric pottery throughout Europe (Craig et al., 2005, 2011; Spangenberg et al., 2008; Isaksson and Hallgren, 2012; Salque et al., 2012; Heron et al., 2015; Cramp et al., 2019; Stojanovski et al., 2020) and it is considered to be one of the main drivers of the introduction of domesticated animals into the subsistence economy (Copley et al., 2003; Dunne et al., 2012). However, direct chemical evidence for the presence of dairy in the Swifterbant culture has been lacking until now. In this study, we present the first evidence for dairy products in two Swifterbant vessels, one from Brandwijk L50 (Fig. 4c) and one possibly from De Bruin phase 3 (Fig. 4b).

One of the biggest challenges now, however, is to understand whether these one or two pots with dairy lipids are an under-representation of the wider use of dairy products in the Swifterbant culture or if they are the results of interactions with neighbouring farmer communities. Traditionally, one of the ways to study dairying is to reconstruct slaughter age and sex profiles based on the animal bones. High abundances of mature females, low numbers of mature males and high abundances of very young animals are seen as evidence for dairying (Payne, 1973). While *Bos* sp. and sheep/goat are present at both De Bruin and Brandwijk (Fig. 5, Fig. 6B; Çakırlar et al., 2019, 2020), the high fragmentation of the remains and the small size of the assemblages prevent us from profiling the age and sex of these animals. As a result, it remains uncertain whether these animals were kept for their meat or were also exploited for secondary products such as milk, butter and cheese.

Another type of analysis focuses on the ceramic characteristics of the vessels directly associated with dairy processing. Both Swifterbant vessel fragments containing dairy products are flask-like, have small diameters and are decorated with bird bone impressions around the neck (Supplementary Dataset-1; Fig. 2, BR08 and HR20). All the other pots from these assemblages have beaker shapes, larger diameters and are never decorated with bird bone impressions. The similarities between these two vessels further strengthens the interpretation of the De Bruin vessel as one involved in dairy processing and the shared notion about the characteristics of 'dairy vessels' between the potters of De Bruin and Brandwijk. This is consistent with the Funnel Beaker flasks from submerged coastal site Neustadt in Schleswig-Holstein, Northern

Germany which were used for processing dairy (Saul et al., 2014). Our findings make further lipid analysis on more Swifterbant flask-like vessels as well as petrographic analysis of these assemblages the logical next step in order to test our results with a bigger data set and also to distinguish whether the 'dairy vessels' were produced on site or are vessels that were brought to the site, with their specific content.

6. Conclusion

The new data presented here clearly shows that processing freshwater fish was a continuous and primary function of Swifterbant pottery in the Lower Rhine-Meuse area, starting from its first appearance at c. 5000 cal BC till the end of 5th millennium BC. We argue that the main use of the pottery for processing freshwater fish among Swifterbant sites was a consistent and deliberate choice which was also maintained while the two main aspects of the Neolithization process (i.e. cereal cultivation and possibly animal husbandry) were introduced to the area. In this regard, our research contributes to the discussion of the pottery production in the hunter-gatherer societies and the function of the pottery through the Mesolithic-Neolithic transition in northern Europe. From our data, we suggest that the Mesolithic-Neolithic transition in the Lower Rhine-Meuse area was not a sudden event but more of a gradual process which was certainly influenced in part by the dynamics of intercultural encounters with neighbouring farming communities.

The results of our analysis also present temporal changes in the exploitation of food resources from the early to the late 5th millennium BC. In addition to the continuous exploitation of freshwater resources, we see that processing ruminant foodstuff becomes an important part of pottery use in the mid-5th millennium BC. Whether this is a result of the arrival of domesticated animals around the same time into the Lower Rhine-Meuse area or is evidence for the continuous exploitation of wild ruminant fauna, it presents a change in the ways of processing ruminant food resources and the use of pottery. This is followed by the first appearance of dairy products in the Swifterbant pottery. Although, at this point, we are not able to fully grasp the scale of dairy production, our study is important in terms of showing the first evidence of processing dairy in the Swifterbant pottery. It also allows us to propose that the De Bruin phase 3 is where we start to see a change in human-animal relations to such extent that we might talk about the start of the Mesolithic-Neolithic transition in the Lower Rhine-Meuse area.

By the late 5th millennium BC, we witness another change in the use of Swifterbant pottery in the Lower Rhine-Meuse area as the ruminant animal carcass fats completely disappear from the pots and get replaced by porcine fats. This kind of a shift in the use of pottery raises questions about changing human-animal relations in terms of animal management and culinary practices in Swifterbant culture. In view of the limited understanding of the animal bones present, lipid residue analysis provides a strong method to gain insights into human-animal relations during the 5th millennium BC.

Another outcome of our study relates the functional variation to the ceramic characteristics of the Swifterbant pottery. It appears that beaker-shaped vessels were used for processing freshwater and terrestrial resources, while processing dairy products was associated with flasks - a pottery shape associated with dairy products in other areas as well (Saul et al., 2014). This is the first time we are able to present functional variation in the Swifterbant pottery through lipid residue analysis. Therefore, this needs to be examined with further research such as petrographic analysis to determine the origin of these "dairy vessels" which would help us to gain insight into the origin of the content of the pots, contributing to the discussion of cultural preferences on culinary practices, human mobility and/or interaction between different groups in the Lower Rhine-Meuse area.

Differences in pottery use between these four Swifterbant sites cannot be explained only by the differences in availability or accessibility of the resources in their immediate or surrounding environment. It is known that diet can relate to different subsistence economies

determined by both local environment and cultural change. However, zooarchaeological and archaeobotanical records present a continuous exploitation of similar and diversified faunal/floral resources in all four sites. Therefore, we argue that different culinary practices developed through the 5th millennium in the Lower Rhine-Meuse area and that the use of Swifterbant pottery may be a direct reflection of changing cultural preferences on food preparation and consumption which requires further research.

Overall, our current study provides an important insight into the function of the hunter-gatherer pottery, broadening our knowledge about the Swifterbant culture north-western Europe. It also shows that additional analysis on the bone material is needed to contribute to the debate of changing human-animal relations and Mesolithic-Neolithic transition in the Swifterbant culture.

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CRedit authorship contribution statement

Özge Demirci: Conceptualization, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Alexandre Lucquin:** Investigation, Writing - review & editing. **Canan Çakırlar:** Validation, Investigation, Writing - original draft, Writing - review & editing. **Oliver E. Craig:** Methodology, Resources, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **Daan C.M. Raemaekers:** Conceptualization, Resources, Validation, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2021.102812>.

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