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## 43 Introduction

44

45 Products from omnivorous animals, such as pigs and poultry, dominate global meat production and are  
46 important for fuelling the next 'Livestock Revolution' in attempts to feed increasing global populations  
47 (Delgado et al., 1999). Undoubtedly, these were also important commodities in many past contexts, as  
48 attested by the frequent occurrence of their skeletal remains on a wide range of archaeological sites  
49 (Maltby, 2014; O'Connor, 2014; Redding, 2015; Sykes, 2012). Whilst it is generally accepted that pig  
50 bones on archaeological sites provide evidence for the consumption of pork products, the use of poultry  
51 in the past is complicated by other historically and ethnographically documented uses, from recreation  
52 to ritual (Sykes, 2012). Even as a foodstuff, poultry have been overlooked and under investigated in the  
53 past despite their undisputed importance today as a major global resource. Therefore, whilst there is  
54 clear faunal evidence attesting to the presence of domestic chicken on European archaeological sites  
55 since later prehistory (Peters et al., 2015; Serjeantson, 2009), it is unclear when, where and why poultry  
56 became routinely raised for their meat and eggs and viewed primarily as a foodstuff. One way to  
57 unequivocally demonstrate this link is by directly associating poultry products with domestic cooking  
58 vessels.

59

60 Archaeological ceramic vessels provide a wealth of information on resource use, offering a window into  
61 past production, storage, transport and processing of food and other commodities. Lipids (fats, oils and  
62 waxes) can be readily absorbed in unglazed, porous ceramic vessels (Evershed et al., 1999), and  
63 preserved for hundreds to thousands of years (Craig et al., 2013). Analytical techniques, involving gas  
64 chromatography (GC) and GC-mass spectrometry (GC-MS), provide a means to associate broad classes  
65 of compounds to their biological precursors (Evershed et al., 1999; Evershed, 2008). Stable carbon  
66 isotope analysis of palmitic ( $C_{16:0}$ ) and stearic ( $C_{18:0}$ ) acids by GC-combustion-stable isotope ratio MS  
67 (GC-c-IRMS) provides a complementary method for animal fat identification in archaeological ceramic  
68 vessels (Copley et al., 2003; Craig et al., 2013; Evershed et al., 2002b; Mukherjee et al., 2008; Salque et  
69 al., 2013). This latter approach is routinely used to identify ruminant products (Craig et al., 2012), and  
70 dairying activity in the archaeological record. However, relatively few studies have considered using this  
71 approach to identify poultry products or distinguish these from other omnivorous animals, such as pigs  
72 (Evershed et al., 2002b).

73

74 In a first attempt to determine the processing of poultry in ceramic vessels, we investigate a pottery  
75 assemblage from the Anglo-Saxon site of Flixborough in North Lincolnshire (England). The site was  
76 chosen as its faunal assemblage shows clear evidence of mixed monogastric and omnivorous animal  
77 exploitation, i.e. geese, chickens, pigs. To distinguish these, we determined carbon isotope values of  
78 fatty acids obtained from archaeological bones of monogastric-omnivorous animals associated with the  
79 pottery to provide *in-situ* reference values. Our aim is to determine whether different monogastric  
80 commodities were processed in ceramic vessels.

81

82 *Isotopic variability in monogastric-omnivorous animal fats*

83

84 The stable carbon isotopic ratios of monogastric and ruminant adipose fatty acids differ due to  
85 fundamental variations in digestive physiology and metabolic processes (Copley et al., 2003; Howland et  
86 al., 2003; Jim et al., 2004; Stott et al., 1997a). Notably, ruminants incorporate specific saturated  
87 compounds (e.g. C<sub>18:0</sub>) directly from their diet into their tissues, following biohydrogenation of the  
88 unsaturated precursors in the rumen (Harrison and Leat, 1975; Krogdahl, 1985). This process leads to  
89 measurable <sup>13</sup>C depletion compared to *de novo* synthesized components (e.g. C<sub>16:0</sub>). However,  
90 distinguishing fat from economically important monogastric and omnivorous animals (e.g. pigs, poultry)  
91 is less straightforward using this approach. Omnivorous animals consume a broader range of food  
92 sources compared to herbivores and consequently the carbon in fatty acids can be derived from a wider  
93 range of macronutrient sources, including lipids, carbohydrates and proteins from both animals and  
94 plants (Budge et al., 2011; Howland et al., 2003; Stott et al., 1997a; Trust Hammer et al., 1998).  
95 Therefore, fatty acids from omnivores exhibit considerably larger isotopic variability (e.g. Delgado-  
96 Chavero et al., 2013; Recio et al., 2013) compared to ruminant and monogastric herbivores, depending  
97 on the animal's diet and therefore husbandry practices. As these are variable in the past and most likely  
98 different from the present, modern references for **omnivores** may be inappropriate and ideally site  
99 specific "*in-situ*" baselines need to be constructed.

100

#### 101 *Archaeological bone as an in-situ baseline for organic residue analysis*

102

103 All previous attempts to interpret fatty acids from archaeological pottery rely on comparison with  
104 reference fats from modern animals raised on known diets and preferably sourced close to the  
105 archaeological sites under investigation (Copley et al., 2003; Dudd and Evershed, 1998; Dunne et al.,  
106 2012; Evershed et al., 2002b; Gregg et al., 2009; Salque et al., 2013; Spangenberg et al., 2006). **In**  
107 **Northern Europe, for example, comparative reference fats are typically derived from animals raised on**  
108 **C<sub>3</sub> vegetation with the assumption that they represent the variety of environmental/dietary conditions**  
109 **experienced by past animals (Dudd and Evershed, 1998). While this is entirely reasonable for herbivore**  
110 **ruminants,** it does not account for the greater variability in the diet of omnivores. **Furthermore** modern  
111 **omnivore** references may not be suitable analogues for animals raised in areas that have undergone  
112 substantial changes in vegetation composition during the Holocene (e.g. Near East, (Goodfriend, 1990);  
113 North Africa, (Castañeda et al., 2009)) or in cultural contexts where foddering strategies are known to  
114 have changed in the past (Hamilton and Thomas, 2012; Madgwick et al., 2012). Both geographic and  
115 temporal variability must be considered in the when deriving suitable isotopic reference ranges in order  
116 to capture environmental and cultural effects. **Finally, the use of modern reference fat inherently**  
117 **implies that animal fat preserved in ceramic vessels originate predominantly, or exclusively, from**  
118 **adipose tissue. Nevertheless, other animal tissues are similarly lipid rich (e.g. bone marrow) and thus are**  
119 **potential sources to the pool of animal fat preserved in ceramic vessels. The boiling of bone to release**  
120 **nutrients, for example in soups and broths, may provide another mechanism for transferring bone lipids**  
121 **to archaeological ceramics.**

122

123 As soft tissues are very rarely preserved in archaeological contexts, animal bone may provide an  
124 alternative **or complementary** source of fatty acids for comparison. Animal bones are often found  
125 directly associated with pottery (i.e. in the same contexts, stratigraphic units or site areas, and in rare

126 instances within the pots themselves) and are therefore chronologically coherent with cultural and  
127 environmental contexts. The lipid composition in adipose tissues and cortical bone are similar in nature  
128 (Kagawa et al., 1996; Ren et al., 2008) and studies have shown that lipids are preserved in archaeological  
129 bone (Evershed et al., 1995b; Spangenberg et al., 2014; Stott and Evershed, 1996). Recently Colonese et  
130 al. (2015) have demonstrated that endogenous palmitic (C<sub>16:0</sub>) and stearic (C<sub>18:0</sub>) fatty acids can be  
131 recovered in sufficient quantity from archaeological bones from a range of environments to permit  
132 stable isotope analysis by GC-C-IRMS. In agreement with earlier studies (Stott et al., 1999, 1997a) it has  
133 been shown that stable carbon isotope composition of bone lipid covariates with bone collagen  
134 (Colonese et al., 2015), supporting the endogenous origin of fatty acids and their potential for  
135 paleodietary reconstruction.

136

## 137 **Flixborough**

138

### 139 *The site and economy*

140

141 Excavations at Flixborough, North Lincolnshire, exposed a high-status Anglo-Saxon site with an  
142 occupation sequence stretching from the 7<sup>th</sup> to 11<sup>th</sup> centuries AD (with subsequent use in the 12<sup>th</sup>- 15<sup>th</sup>  
143 centuries) (Loveluck and Gaunt, 2007; Loveluck, 1998). Over 200,000 fragments of animal bone were  
144 recovered from Flixborough, making it one of the largest assemblages of Middle to Late Anglo-Saxon  
145 date in England (Jaques et al., 2007). A hand-collected and coarse-sieved assemblage of over 41,000  
146 mammal and bird bone fragments dating from the early 7<sup>th</sup> to late 10<sup>th</sup> century was identified to taxon.  
147 The most numerous domesticates (average %NISP) were cattle (*Bos taurus*, 29.4%), followed by  
148 sheep/goat (*Ovis aries/Capra hircus*, 27%), pig (*Sus scrofa domesticus*, 19.4%), chicken (*Gallus gallus*  
149 *domesticus*, 15%), and goose (*Anser* sp., 9.2%) respectively, although the relative proportions of these  
150 changed through time at the site (Jaques et al., 2007).

151

152 Whilst cattle and sheep/goat could have provided multiple secondary products such as milk, wool and  
153 traction, pigs would have primarily been a meat resource. Chickens would have been a useful source of  
154 meat and feathers, but also important for providing eggs and potentially fertiliser in the form of dung.  
155 However, so far the role of ceramic vessels for processing and preparing these various animal products  
156 has been only preliminarily considered (Young and Vince, 2009). In particular, the identification of  
157 domestic poultry in pottery would help clarify their role at the site and provide the first insights into the  
158 material culture associated with their processing.

159

## 160 **Material and methods**

161

### 162 *Modern samples*

163

164 In order to confirm the utility of bone lipids as reference samples, differences in  $\delta^{13}\text{C}$  values of C<sub>16:0</sub> and  
165 C<sub>18:0</sub> between adipose (subcutaneous and skin fat) and bone lipid was investigated in three distinct  
166 groups of modern chickens raised in Britain. Specimens were slaughtered for commercial purposes or  
167 died of natural causes before the experiment. Group 1 includes 10-week old, free range specimens

168 acquired from an organic farm in Yorkshire (CH-FR, n = 10). These specimens were fed on organic, C<sub>3</sub>-  
169 plant derived pellets and grass; Group 2 includes 4-week old, commercial non-free range broilers (fresh  
170 class A), from a big-chain supermarket (CH-SP, n = 5); Group 3 includes >28-week old, non-commercial  
171 free-range specimens, fed *ad libitum* with occasional supplements of mealworms (CH-D, n = 8).  
172 Unfortunately the adipose tissue for the Group 3 was not available and could not be sampled. However  
173 the bone isotope data was included to explore variability between the populations. Bone lipid  $\delta^{13}\text{C}$   
174 values are also compared with previously reported values from chicken adipose tissues (Dudd and  
175 Evershed, 1998; Evershed et al., 2002b), which were 3-week old broilers fed with pellets. Chicken  $\delta^{13}\text{C}$   
176 values from Dudd and Evershed (1998) were corrected for the effect of modern atmospheric  $\delta^{13}\text{C}$  values  
177 by 1.2‰ (Dudd and Evershed, 1998; Friedli et al., 1986). In chickens, *de novo* synthesis of fatty acids  
178 occurs mainly in the liver and it is transferred by lipoproteins to the site of deposition, whereas in pig it  
179 takes place mainly in the adipose tissue, similar to ruminants (Lalot et al., 2010). In order to  
180 investigate any isotopic differences in fatty acids associated with biosynthesis, subcutaneous adipose  
181 and bone lipids were also investigated in commercial non-free range pigs from several supermarkets and  
182 a local butcher in York (Pig-SP, n = 5). The stable carbon and nitrogen isotope composition of bone  
183 collagen was also analyzed from the modern specimens and compared with bone lipid  $\delta^{13}\text{C}$  values.

184

#### 185 *Archaeological samples*

186

187 Animal bones retrieved from external refuse contexts at Flixborough (5983, 5653), dated to mid-8th to  
188 early-9th century (phase 3biv), were selected for collagen and bone lipid stable isotopic analysis. These  
189 included chicken (Chk, n = 10), goose (Gos, n = 10) and pig (Pig, n = 5). Whenever possible, samples were  
190 selected to represent individual animals by sampling the same-sided portion of a specific element.  
191 Ceramic vessels (n = 60) from 25 Anglo-Saxon contexts were selected for molecular and isotopic analysis  
192 of extracted lipids (Tab. 5). These contexts were selected due to their high relative abundances of  
193 chicken remains (i.e. phase 3i) and good preservation of ceramic vessels, that allowed comparison of  
194 organic residues against pottery size, shape and form. Where possible potsherds were assigned to small,  
195 medium and large sized jars and bowls (Maxey type fabric B, E, U; Tab. 5; Young and Vince, 2009).

196

#### 197 *Collagen extraction of modern and archaeological bones*

198

199 After manually removing the adipose tissue and the bone marrow, modern chicken (ulnae and femora)  
200 and pig (ribs) bones were defatted. Lipids were removed with repeated rinses (x3) of a 2:1  
201 dichloromethane:methanol solvent solution (DCM:MeOH; 3x2 mL), ultrasonicated for 15 min and  
202 centrifuged (850 g) for 10 min. Samples were then rinsed with deionized water and dried at room  
203 temperature. Collagen extraction of archaeological and modern bone followed a modified Longin  
204 method (Brown et al., 1988) and details can be found in previous studies (e.g. (Craig et al., 2010)).  
205 Briefly, shards of modern (~100 - 186 mg) and archaeological bones (245 - 630 mg) were demineralised  
206 using 0.6 M HCl, at 4°C for several days. Samples were then rinsed with distilled water and gelatinised  
207 with 0.001 M HCl at 80°C for 48 h. Initially, the supernatant containing the collagen of modern bones  
208 were ultrafiltered (30 kDa, Amicon® Ultra-4 centrifugal filter units; Millipore, MA, USA). Given that the  
209 bones were modern, or very well-preserved, the remaining samples were filtered using Polyethylene

210 Ezee filters (Elkay Laboratories Ltd., 9 mL, pore size 60-90  $\mu\text{m}$ ). There were not isotopic differences  
211 between ultrafiltered and non-ultrafiltered samples (t-test,  $t = -1.44$ ;  $p = 0.223$ ;  $t = -1.78$ ;  $p = 0.148$ ), in  
212 agreement with previous studies (Sealy et al., 2014). Samples were then frozen and lyophilised.

213

#### 214 *Lipid extraction: bone, adipose tissue and potsherds*

215

216 Lipids were extracted from archaeological (~160 - 580 mg) and modern bones free of marrow (~20 - 250  
217 mg) following a two-step method (Colonese et al., 2015). Archaeological and modern bones were rinsed  
218 several times in distilled water. Archaeological bones were dried at room temperature while modern  
219 bones were frozen and subsequently freeze-dried. Mechanically cleaned chunks or coarsely ground  
220 bones were lipid-extracted using the same procedure as for defatting modern bones (see above).  
221 Exogenous lipids were first removed with 2:1 DCM:MeOH (3x2 mL) from each bone sample. The  
222 supernatant was removed, discarded and the bone powder was dried completely under a gentle stream  
223 of  $\text{N}_2$ . The remaining bone samples were lipid-extracted using acidified methanol (e.g. Correa-Ascencio  
224 and Evershed, 2014; Craig et al., 2013). After adding 2 mL of methanol, the samples were ultrasonicated  
225 for 15 min. Subsequently, 400  $\mu\text{L}$  of  $\text{H}_2\text{SO}_4$  was added and the samples were heated at  $70^\circ\text{C}$  for 4 h. The  
226 samples were then centrifuged (850 xg) for 5 min. The supernatant was extracted with hexane ( $3 \times 2$   
227 mL) and neutralised with  $\text{K}_2\text{CO}_3$ . The extracts were then dried under a gentle stream of  $\text{N}_2$  and an  
228 internal standard (10  $\mu\text{g}$  hexatriacontane) added to each sample before further analysis by GC/MS and  
229 GC/C/IRMS. The same method (acidified methanol) was applied for the subcutaneous adipose tissue (5  
230 and 100 mg), after tissues were rinsed repeatedly with deionized water, frozen and lyophilised.

231

232 Ceramic powder drilled (d. 2mm-5mm) from the internal sherd surface (~1 g) was lipid-extracted using  
233 the methanol (4 mL) and  $\text{H}_2\text{SO}_4$  (800  $\mu\text{L}$ ) procedure as for bone lipids. A selection of samples ( $n = 10$ )  
234 were solvent extracted (DCM:MeOH; 2:1 vol/vol, 3x2 mL, 15 min) using established protocols (e.g.  
235 Dunne et al., 2012). These were silylated N,O-bis(trimethylsilyl)trifluoroacetamide at  $70^\circ\text{C}$  for 1 h and  
236 analysed by high temperature GC (HT-GC) to determine the presence of any acyl lipids (mono-, di- and  
237 triglycerides).

238

239 Bone, adipose tissue and potsherd samples were screened by GC using an Agilent 7890A gas  
240 chromatograph (Agilent Technologies, Cheshire, UK). The injector was splitless and maintained  
241 at  $300^\circ\text{C}$  and injected 1  $\mu\text{L}$  of sample into the GC. The column used was a 100% Dimethylpolysiloxane  
242 DB-1 (15 m x 320  $\mu\text{m}$  x 0.1  $\mu\text{m}$ ; J&W Scientific, Folsom, CA, USA). The carrier gas was hydrogen with a  
243 constant flow rate of 2ml/min. The temperature program was set at  $100^\circ\text{C}$  for 2 minutes, rising by 20  
244  $^\circ\text{C}/\text{min}$  until  $325^\circ\text{C}$ . This temperature was maintained for 3 minutes. The total run time was 16.25 mins.  
245 The lipids were quantified according to the internal standard and diluted appropriately prior to GC-MS  
246 and GC-c-IRMS as described below. To avoid co-elution, samples with a higher concentration of  $\text{C}_{18:1}$   
247 were also treated with  $\text{AgNO}_3$  to isolate the saturated counterpart prior to isotopic analysis. Stable  
248 isotope values of paired samples did not show evidence of isotopic fractionation between  $\text{AgNO}_3$   
249 treated and untreated samples.

250

#### 251 *Carbon and nitrogen stable isotope analysis of bulk collagen*

252  
253 Collagen samples (1 mg) were analysed in duplicate or triplicate by EA-IRMS in a GSL analyser coupled to  
254 a 20-22 mass spectrometer (Sercon, Crewe, UK) at the University of York. The analytical error for both  
255  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values, calculated from repeated measurements of each sample and measurements of the  
256 bovine control from multiple extracts, was  $<0.2\%$  ( $1\sigma$ ).  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N} = [(R_{\text{sample}}/R_{\text{standard}} - 1)] \times 1,000$ ,  
257 where  $R = {}^{13}\text{C}/{}^{12}\text{C}$  and  ${}^{15}\text{N}/{}^{14}\text{N}$ . The standard for  $\delta^{13}\text{C}$  is Vienna PeeDee Belemnite (V-PDB), the standard  
258 for  $\delta^{15}\text{N}$  is air  $\text{N}_2$ . In-house collagen standards (bovine control) were exchanged between laboratories  
259 (University of Bradford) to ensure accuracy.

#### 260 261 *Gas chromatography-mass spectrometry (GC-MS)*

262  
263 GC-MS was carried out on all samples using a 7890A Series chromatograph attached to a 5975C Inert XL  
264 mass-selective detector with a quadrupole mass analyser (Agilent Technologies, Cheadle, UK). The  
265 carrier gas used was helium, and the inlet/column head-pressure was constant. A splitless injector was  
266 used and maintained at  $300^\circ\text{C}$ . The GC column was inserted directly into the ion source of the mass  
267 spectrometer. The ionisation energy of the mass spectrometer was 70 eV and spectra were obtained by  
268 scanning between  $m/z$  50 and 800. Three different analytical columns were used.

269  
270 General screening was performed using a DB-5ms (5%-phenyl)-methylpolysiloxane column ( $30\text{ m} \times$   
271  $0.250\text{ mm} \times 0.25\ \mu\text{m}$ ; J&W Scientific, Folsom, CA, USA). The temperature for this column was set at  $50^\circ\text{C}$   
272 for 2 min, then raised by  $10^\circ\text{C min}^{-1}$  to  $325^\circ\text{C}$ , where it was held for 15 min. [This column was also used](#)  
273 [with the MS in Single Ion Monitoring \(SIM\) mode to selectively detect ions characteristics of alkylphenyl](#)  
274 [alkanoic acids \(APAAs;  \$m/z\$  105,  \$m/z\$  262,  \$m/z\$  290,  \$m/z\$  318\) in order to increase the sensitivity for the](#)  
275 [detection of lipids derived from aquatic products \(Evershed et al., 2008; Hansel et al. 2004\). For this](#)  
276 [purpose, the temperature was set at  \$120^\circ\text{C}\$  for 2 min, raised by  \$6^\circ\text{C min}^{-1}\$  to  \$260^\circ\text{C}\$ , and then raised by](#)  
277  [\$20^\circ\text{C min}^{-1}\$  to  \$325^\circ\text{C}\$  where it was held for 10 min.](#)

278  
279 A second, more polar column (DB-23, 50%-cyanopropyl-methylpolysiloxane,  $60\text{ m} \times 0.25\text{ mm} \times 0.25\ \mu\text{m}$ ;  
280 J&W Scientific) was used to provide better resolution of isoprenoid fatty acids. The temperature was set  
281 at  $50^\circ\text{C}$  for 2 min, raised by  $10^\circ\text{C min}^{-1}$  to  $100^\circ\text{C}$ , then raised at  $4^\circ\text{C min}^{-1}$  to  $250^\circ\text{C}$ , where it was held for  
282 20 min. [This column was also used with the MS in Single Ion Monitoring \(SIM\) mode to selectively detect](#)  
283 [ions characteristics of APAA \( \$m/z\$  105,  \$m/z\$  262,  \$m/z\$  290,  \$m/z\$  318\).](#)

284  
285 Solvent extracted samples were analyzed with a HT-DB1, 100% Dimethylpolysiloxane ( $15\text{ m} \times 0.320\text{ mm}$   
286  $\times 0.1\ \mu\text{m}$ ) (J&W Scientific, Folsom, CA, USA). The injector was maintained at  $350^\circ\text{C}$ . The temperature of  
287 the oven was set at  $50^\circ\text{C}$  for 2 min, and then raised by  $10^\circ\text{C min}^{-1}$  to  $350^\circ\text{C}$ , where it was held for 15 min.

#### 288 289 *Gas chromatography-combustion-isotope ratio mass spectrometry (GC-c-IRMS)*

290  
291 Carbon stable isotopes were determined on two fatty acid methyl esters; methyl palmitate ( $\text{C}_{16:0}$ ) and  
292 methyl stearate ( $\text{C}_{18:0}$ ) in each extract using an Isoprime 100 (Isoprime, Cheadle, UK) linked to a Hewlett  
293 Packard 7890B series gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) with a Isoprime



294 GC5 interface (Isoprime, Cheadle, UK). The gases eluting from the chromatographic column were split  
295 into two streams. One of these was directed into an Agilent 5975C inert mass spectrometer detector  
296 (MSD), for sample identification and quantification, while the other was directed through the GC5  
297 furnace held at 850°C to oxidise all carbon species into CO<sub>2</sub>. All samples were diluted with hexane and  
298 subsequently 1 µL of each sample was injected into a DB-5MS fused-silica column. The temperature was  
299 set for 0.5 minute at 50°C, and raised by 10°C min<sup>-1</sup> until 300°C was reached, at which it stayed for 10  
300 minutes. The carrier gas was ultra-high purity grade helium with a flow rate of 3 mL min<sup>-1</sup>. Eluted  
301 products were combusted to CO<sub>2</sub> and ionized in the mass spectrometer by electron impact. Ion  
302 intensities of m/z 44, 45, and 46 were monitored in order to automatically compute the <sup>13</sup>C/<sup>12</sup>C ratio of  
303 each peak in the extracts. Computations were made with IonVantage Software (Isoprime, Cheadle, UK)  
304 and were based on comparisons with a standard reference gas (CO<sub>2</sub>) of known isotopic composition that  
305 was repeatedly measured. The results from the analysis are reported in parts per mil (‰) relative to an  
306 international standard (V-PDB). Replicate measurements of each sample and a mixture of fames fatty  
307 acid methyl esters (FAMES) with δ<sup>13</sup>C values traceable to international standards were used to  
308 determine instrument precision (<0.3‰) and accuracy (<0.5‰). Values were also corrected subsequent  
309 to analysis to account for the methylation of the carboxyl group that occurs during acid extraction.  
310 Corrections were based on comparisons with a standard mixture of C<sub>16:0</sub> and C<sub>18:0</sub> fatty acids of known  
311 isotopic composition processed in each batch as a sample.

312

### 313 *Statistical analysis*

314

315 Fatty acid δ<sup>13</sup>C values from bone and adipose tissue in modern chicken and pig samples were compared  
316 using a **paired t-test (after checking for equality of variance with F test)** in PAST 3.x (Hammer et al.,  
317 2001).

318 **Theoretical mixing curves were computed in order to estimate the effect of mixing of different animal**  
319 **fats on the fatty acid δ<sup>13</sup>C values of ceramic sherds (e.g. Dudd 1990; Evershed 2008; Mukherjee et al.,**  
320 **2008). Four mixing curves were computed between chicken and pig, goose, ruminant adipose and milk**  
321 **fat. This approach takes into account the average δ<sup>13</sup>C values and the relative abundance of C<sub>16:0</sub> and**  
322 **C<sub>18:0</sub> fatty acids from each animal fat. Fatty acid δ<sup>13</sup>C values for goose, pig, and chicken were taken from**  
323 **the archaeological bones, while fatty acid δ<sup>13</sup>C values for ruminant adipose and milk were sourced from**  
324 **the literature (Dudd and Evershed 1999). The relative proportions of C<sub>16:0</sub> and C<sub>18:0</sub> fatty acids (average %**  
325 **of free fatty acid distribution) were taken from Dudd (1990).**

326

## 327 **Results and discussion**

328

### 329 *Molecular and stable isotope composition of modern bone and adipose tissue*

330

331 Derivatized fatty acids from bone and adipose tissues were similar for both chicken and pig samples (Fig.  
332 1A-B), except for a lower concentration of unsaturated and polyunsaturated fatty acids recovered in  
333 bone, which can be in part attributed to the solvent wash. Similar results were obtained for pig samples.  
334 In chicken and pig the main lipids extracted were C<sub>18:1</sub>, C<sub>16:0</sub>, C<sub>18:0</sub>, C<sub>18:2</sub>, C<sub>20:4</sub>. In chicken these were  
335 followed by other saturated (C<sub>12:0</sub> to C<sub>24:0</sub>), monounsaturated (C<sub>14:1</sub>, C<sub>17:1</sub>), polyunsaturated fatty acids

336 ( $C_{20:2}$ ,  $C_{20:3}$ ,  $C_{20:5}$ ) and cholesterol derivatives (particularly in bone; Evershed et al., 1995b). The fatty acid  
337 distribution is consistent with poultry fat reported in the literature (Givens et al., 2011; Koizumi et al.,  
338 1991) and some variations in relative abundance between groups most likely reflect diversification in  
339 dietary components (Crespo and Esteve-Garcia, 2002). In pig samples, other extracted lipids also include  
340 saturated ( $C_{12:0}$  to  $C_{24:0}$ ), monounsaturated ( $C_{17:1}$  to  $C_{24:1}$ ), polyunsaturated fatty acids ( $C_{20:2}$ ,  $C_{20:3}$ ,  $C_{20:5}$ ,  
341  $C_{22:4}$ ,  $C_{22:5}$ ,  $C_{22:6}$ ) and cholesterol derivatives (bone).

342  
343 The  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  in bone and adipose tissues are reported in Table 1. Free range organic  
344  $C_3$  specimens (Group 1) have average  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  in subcutaneous fat ( $-29.2\pm 1.0\text{‰}$  and  $-$   
345  $28.9\pm 1.2\text{‰}$  respectively) statistically indistinguishable from bone ( $-29.0\pm 0.9\text{‰}$  and  $-28.5\pm 0.7\text{‰}$ ) (paired  
346 t-test,  $t = -1.018$ ,  $p = 0.335$  and  $t = -1.659$ ,  $p = 0.131$  respectively), with mean pairwise differences in  $\delta^{13}C$   
347 between adipose and bone lipids of  $0.2\text{‰}$  and  $0.4\text{‰}$  for  $C_{16:0}$  and  $C_{18:0}$  respectively. In commercial non-  
348 free range chickens (Group 2), the average  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  are significantly lower in adipose  
349 tissue ( $-29.2\pm 0.6\text{‰}$  and  $-29.4\pm 0.4\text{‰}$ ) compared to bone ( $-28.5\pm 0.3$  and  $-28.3\pm 0.3\text{‰}$ ) by  $0.8\text{‰}$  (paired t-  
350 test,  $t = -6$ ,  $p = 0.003$ ) and  $1.1\text{‰}$  ( $t = -7.78$ ,  $p = 0.001$ ) respectively. No significant differences were  
351 observed in the distribution of  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  between adipose tissue ( $-29.3\pm 0.6\text{‰}$  and  $-$   
352  $28.4\pm 0.6\text{‰}$ ) and bone ( $-29.5\pm 0.7\text{‰}$  and  $-28.6\pm 0.3\text{‰}$ ) from commercial pork samples (paired t-test,  $t$   
353  $= 1.15$ ,  $p = 0.327$  and  $t = -1.17$ ,  $p = 0.304$  respectively). The small isotopic offset between adipose and  
354 bone lipid in chicken noticed in Group 2 might reflect differential turnover rate and isotopic  
355 fractionation during *de novo* synthesis and assimilation from diet of fatty acid in liver, bone and adipose  
356 tissue (Nir et al., 1988). However, we note that the magnitude of the adipose/bone pairs is not great.

357  
358 Comparisons between bone fatty acid  $\delta^{13}C$  values reveal no overall differences between specimens from  
359 Groups 1 and 2 (organic free range and battery) for both  $C_{16:0}$  ( $t = -1.18$ ,  $p = 0.256$ ) and  $C_{18:0}$  ( $t = -0.61$ ,  $p =$   
360  $0.549$ ; Fig. 2). By contrast, non-commercial free-range specimens (Group 3) have  $\delta^{13}C$  values of  $C_{16:0}$  and  
361  $C_{18:0}$  in bone ( $-25.4\pm 0.6\text{‰}$  and  $-25.8\pm 0.9\text{‰}$ ) significantly higher than specimens from both groups 1 and  
362 2 ( $p < 0.005$  for both groups). Average  $\delta^{13}C$  values of  $C_{16:0}$  ( $-30.2\text{‰}$ ) and  $C_{18:0}$  ( $-29.4\text{‰}$ ) in adipose chicken  
363 fat reported by Dudd and Evershed (Dudd and Evershed, 1998) also differ statistically from bone lipid  
364 from groups 1, 2 and 3 ( $p < 0.005$  for all groups). The dietary regimes the animals were reared under  
365 have a clear effect on the isotopic composition of their fatty acid values.

366  
367 In agreement with previous studies (Colonese et al., 2015; Stott et al., 1997b) both  $C_{16:0}$  and  $C_{18:0}$  are  
368 depleted in  $^{13}C$  relative to bulk collagen from the same samples (Tab. 2). However, the range of the  
369 offset (ca.  $3\text{‰}$  to  $7\text{‰}$ ) is greater than previously observed. The isotopic offset fundamentally reflects  
370 differences between the biosynthesis of collagen and fatty acids, and particularly the kinetic isotopic  
371 fractionation associated to the oxidative decarboxylation of pyruvate to acetyl Co-A during lipid  
372 biosynthesis (DeNiro and Epstein, 1977). Strong positive correlations between bone lipid and collagen  
373  $\delta^{13}C$  and  $\delta^{15}N$  values confirm that the lipids are endogenous (Fig. 3).

374 The results indicate that the  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  in bone reflect the isotopic composition of  
375 adipose fat in chicken and pig samples. Therefore, we conclude that fatty acids from bone are a suitable  
376 reference for comparison with adipose derived fatty acids extracted from archaeological pottery.

377

378 *Molecular and stable isotope composition of archaeological bone*

379

380 The lipid extracts from archaeological bones (chicken, goose, pig) are in general dominated by saturated  
381 fatty acids ( $C_{12:0}$  to  $C_{28:0}$ ), notably  $C_{16:0}$  and  $C_{18:0}$ , and by lower concentrations of monounsaturated fatty  
382 acids (particularly  $C_{18:1}$ ), along with some products of cholesterol oxidation (cholesta-3,5-diene;  
383 Evershed et al., 1995b). Traces of linoleic acid ( $C_{18:2}$ ) were present in chicken, pig and goose bones, while  
384 phytanic acid (3,7,11,15-tetramethylhexadecanoic acid) was recorded in all goose bones. These  
385 compounds are compelling evidence for the endogenous origin of lipids in the bone as they can only be  
386 incorporated through diet and **are rare in the depositional environment**. Phytanic acid in the goose  
387 samples is likely to be attributable to the direct ingestion of aquatic organisms (zooplanktons) (Lucquin  
388 et al., 2016; van den Brink et al., 2004; Wanders et al., 2011).

389

390 Archaeological bones yielded sufficient amounts of fatty acids for stable carbon isotopic analysis (Tab.  
391 3). **No significant correlations were observed between total fatty acid yield ( $\mu\text{g g}^{-1}$ ) and the  $\delta^{13}\text{C}$  values**  
392 **for both  $C_{16:0}$  ( $R^2 = 0.04$ ,  $p = 0.30$ ) and  $C_{18:0}$  ( $R^2 = 0.10$ ,  $p = 0.11$ ) respectively. Similarly, no significant**  
393 **correlation was observed between  $C_{16:0}$  yields and their  $\delta^{13}\text{C}$  values ( $R^2 = 0.13$ ,  $p = 0.06$ ), while significant**  
394 **but a very weak correlation was found between  $C_{18:0}$  yields and their  $\delta^{13}\text{C}$  values ( $R^2 = 0.20$ ,  $p = 0.02$ ).**  
395 **The results confirm that degradation of fatty acids have no effect on their stable carbon isotope**  
396 **composition, as already demonstrated for fatty acids preserved in archaeological ceramics (e.g.**  
397 **Evershed et al., 1999). Furthermore moderate to high correlations between fatty acid and collagen  $\delta^{13}\text{C}$**   
398 **values (Fig. 4) support the preservation of lipids in our archaeological bone assemblages, as observed in**  
399 **previous studies (Colonese et al., 2014). The  $\delta^{13}\text{C}$  values of archaeological bone lipids are compared with**  
400 **modern authentic carcass fat and milk for the UK (Copley et al., 2003; Dudd and Evershed, 1998;**  
401 **Evershed et al., 2002a) from ruminant and monogastric-omnivorous animals raised on  $C_3$  plants (Fig. 5).**  
402 **As the diet between ancient and modern herbivores is unlikely to be very different in this context, we**  
403 **consider these values to be a suitable proxy.**

404

405 The  $\delta^{13}\text{C}$  values of  $C_{16:0}$  and  $C_{18:0}$  in archaeological goose bone differ to those from UK modern  
406 references. There is larger variability in archaeological samples, which probably reflects different  
407 management strategies and environments, or potentially the presence of both wild and domestic geese  
408 in the archaeological sample (Budge et al., 2011; Trust Hammer et al., 1998). Finally, substantial isotopic  
409 differences are also observed between omnivorous animals, notably chickens and pigs. Although pigs  
410 and chickens were being raised at elite settlements, historical documents indicate that pigs were often  
411 supplied by lower status people to elites as food rents, with chickens also being provided in this manner  
412 (Hagen, 1995). Accordingly, the observed isotopic differences may in part reflect different management  
413 strategies by groups not resident at Flixborough.

414

415 Fatty acids from archaeological pig bones have  $C_{16:0}$  and  $C_{18:0}$  consistently depleted in  $^{13}\text{C}$  by  $\sim 3\text{‰}$   
416 compared to those from modern pigs originating from the UK, but are within the observed range of  $\delta^{13}\text{C}$   
417 values for Central Europe (Spangenberg et al., 2006). Archaeological pig bones also have narrower  $\delta^{13}\text{C}$   
418 values in both  $C_{16:0}$  ( $0.4\text{‰}$ ) and  $C_{18:0}$  ( $0.6\text{‰}$ ) than the modern reference fat. By contrast, the  $\delta^{13}\text{C}$  values  
419 of  $C_{16:0}$  in chicken bones from Flixborough are higher by  $\sim 2\text{‰}$  compared to the modern chicken sample.

420 Differences between archaeological and modern samples may be related to differences in foddering  
421 practices and access to food sources with variable lipid content and isotopic signatures. Most likely,  
422 archaeological pigs and chickens were raised on a mixture of plants and animal products, however  
423 measurable differences between pigs and chickens also point toward species-specific husbandry  
424 practices. This is further supported by collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values (Fig. 6), which reveal that chickens  
425 had access to food sources at a higher trophic position than pigs or their diet contained a higher  
426 proportion of animal to plant products. Pathological data provide further information about how pigs  
427 were raised at Flixborough. Frequencies of Linear Enamel Hypoplasia on pig teeth indicate the  
428 Flixborough pigs were kept in a semi-natural husbandry regime, including use of a woodland  
429 environment, which provided suitable foraging opportunities for the pigs (Dobney et al., 2002).  
430 Interestingly, O'Connell and Hull's (2011) synthesis of animal isotope data from the Anglo-Saxon period  
431 (predominantly Early and Middle-Saxon) indicated that the degree of omnivory among the pigs was not  
432 high, showing some overlap with sheep and cattle. This was consistent with the pigs being raised in a  
433 free-range system, including pannage. The chickens and geese in their samples also have elevated  $\delta^{15}\text{N}$   
434 values compared to other species. Data from Flixborough thus supports the view that chickens were  
435 generally raised in local/household settings, while pigs had greater access to woodland products and  
436 higher plant content in their diet.

437  
438 The contribution of animal products to chicken diet would be further confirmed by the correlations  
439 between  $\delta^{13}\text{C}$  of fatty acids and collagen (Fig. 4). The high correlation between  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  
440 collagen reveals that the  $\text{C}_{16:0}$  fatty acid in pig, chicken and goose bones was predominantly synthesized  
441 *de novo* from carbohydrates and protein precursors. By contrast the lower correlation observed  
442 between  $\delta^{13}\text{C}$  values of  $\text{C}_{18:0}$  and collagen, mainly due to an overall  $^{13}\text{C}$ -depletion in the  $\text{C}_{18:0}$  fatty acid of  
443 chickens is more difficult to explain. It could imply some degree of direct incorporation of  $\text{C}_{18:0}$  fatty acid  
444 in chicken bone from diet (Baião and Lara, 2005; Villaverde et al., 2006).

#### 445 446 *Molecular and stable isotope composition of organic residues in archaeological ceramics*

447  
448 Appreciable amounts of absorbed lipids could be extracted from the vast majority of analyzed potsherds  
449 (90%, n = 54), demonstrating relatively good preservation, with concentrations up to  $\sim 2 \text{ mg g}^{-1}$  (average  
450  $1.02 \text{ mg g}^{-1}$ ) compared to other studies (Evershed, 2008; Evershed et al., 2008). They revealed a range of  
451 saturated and unsaturated mid-chain length n-alkanoic acids (fatty acids) with even numbers of carbon  
452 atoms, particularly dominated by  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  (Tab. 5; Fig. 7). Most of these samples contain trace  
453 amounts of isoprenoid fatty acids (phytanic acid), short chain diacids, scarce amounts of cholesterol and  
454 mid-chain ketones. These compounds demonstrate that the vessels were used for heating animal fat,  
455 possibly along with plant resources (Baeten et al., 2013; Evershed et al., 1995a; Raven et al., 1997).  
456 Traces of  $\text{C}_{16}$  and  $\text{C}_{18}$   $\omega$ -(o-alkylphenyl) alkanolic acids (APAAs), likely formed from mono- di and tri-  
457 unsaturated fatty acid precursors (Hansel et al., 2004) were found in most of the sherds, along with  
458 short-chain alkanes. Significantly however, longer chain length APAAs typically formed from processing  
459 aquatic organisms (Evershed et al. 2008) were absent, even when the MS was used to selectively  
460 monitor ions from these compounds thereby maximising the chance of detection. Other lipids at high

461 concentration in aquatic tissues, such as 4,8,12-TMTD (Hansel et al. 2004), were also absent. Therefore  
462 there is no evidence that fish were processed in pottery from Flixborough.

463  
464 Triacylglycerols (TAGs) were recovered from only two sherds out of ten that were tested using solvent  
465 extraction. The acyl carbon distribution of TAGs in these samples ( $C_{42}$ - $C_{50}$  and  $C_{46}$ - $C_{54}$ ) is consistent with  
466 dairy and ruminant adipose fat respectively, and this inference is supported by their  $\delta^{13}C$  values of  $C_{16:0}$   
467 and  $C_{18:0}$ . Apart from these observations, there were no other compounds that could be used to further  
468 resolve the source of the residue. Most likely, extensive degradation has substantially altered the  
469 original lipid distributions.

470  
471 Identification of the degraded animal fats recovered from the pottery was assessed through the  
472 determination of the  $\delta^{13}C$  values of  $C_{16:0}$  and  $C_{18:0}$  (Tab. 5). The results were compared with fatty acid  
473  $\delta^{13}C$  values from archaeological bones (pig, chicken, goose) and modern ruminant adipose and milk  
474 reference for the UK (Dudd and Evershed 1999). Over half of the potsherds (62.9%) have fatty acid  $\delta^{13}C$   
475 values broadly consistent with modern ruminant adipose fat (Fig. 8). However, as these values fall  
476 between the ellipses of modern ruminant adipose and dairy as well as archaeological monogastric-  
477 omnivore bone fats, mixing of these commodities would produce similar results. Such equifinality  
478 cannot be easily resolved. The remaining potsherds have fatty acid  $\delta^{13}C$  values that fall within the  
479 reference ranges for archaeological bone fat from pig and goose (16.6%), chicken (9.25%) and modern  
480 ruminant milk (7.4%). Notably, the three vessels that produced almost identical values to archaeological  
481 chicken bones are from the 8-9th century phase (Fig. 8). These data are not as easily explained by mixing  
482 of different fats. From theoretical mixing curves, it is crudely estimated that these three ceramic sherds  
483 must contain at least 90% chicken fat if mixed with pig/goose or ruminant carcass fat (Fig 8). Modelling  
484 mixtures of other fats (curves not shown) does not produce values that plot within the chicken ellipse.

485 The results therefore would represent the first direct identification of poultry lipids in archaeological  
486 ceramic vessels and implies that these three vessels, at least, were used largely for this purpose.  
487 However, further consideration of uncertainties associated with the reference ranges of different fatty  
488 acids in the source fats and their concentration is needed to discern the degree to which other  
489 commodities may have been mixed in these vessels. The deconvolution of multiple sources requires the  
490 development and application of more sophisticated mixing models.

491  
492 The vessel typology was only evident in approximately half of vessels that produced interpretable lipid  
493 residues but some preliminary observations could still be made (Tab. 5). For example, residues from the  
494 omnivorous animals were only clearly distinguishable in jars, which generally had a wider range of uses  
495 compared to bowls. Similar results were observed in the early medieval site of West Cotton, in Britain,  
496 where jars contained the largest range of lipid compounds and may have had a more versatile function  
497 compared to other vessels (Charters et al., 1993). By contrast, pottery size and fabric did not influence  
498 lipid distribution and isotopic composition.

499  
500 Study of the faunal bone assemblage from Flixborough has shown that animal exploitation was mainly  
501 focused on cattle and sheep, followed by pigs and poultry (chicken, geese) in the mid-8<sup>th</sup> to early 9<sup>th</sup>  
502 century. Organic residue analysis demonstrates that all these animals were indeed processed in ceramic

503 containers, as well as dairy products, as may have been expected. The pottery evidence shows that  
504 poultry were processed in the same way and probably mixed with multiple products from other  
505 livestock and perhaps perceived similarly, at least in terms of their culinary value. However, it is  
506 important to point out that using this isotopic approach we cannot differentiate lipids derived from  
507 chicken eggs or meat. Ruminant products (meat and/or dairy) appears to be the most frequently  
508 processed animal resource in ceramic containers, followed by dairy products and then omnivorous  
509 animals, including chickens, which to some extent show some similarities with the relative abundance of  
510 faunal remains (Jaques et al., 2007). However, further determination of the proportional contribution of  
511 poultry and other products to the pottery at Flixborough currently lacks accurate quantification using  
512 the approach we have described.

513

#### 514 *Archaeological implications*

515

516 This study emphasises further the value of conducting isotopic analyses of residues and integrating  
517 zooarchaeological remains and ceramic artefacts. Compared to larger mammals such as cattle, sheep  
518 and pig, bird bones are often overlooked during excavation because of their small size and therefore  
519 potentially under-represented in many zooarchaeological assemblages. Similarly, avian products are  
520 rarely considered in studies of pottery use or when reconstructing human diet using stable isotopes. As  
521 the wider zooarchaeological evidence from England reveals a considerable increase in chicken remains  
522 from the early to the Late Anglo-Saxon period (Holmes, 2014), poultry products may have been a  
523 common commodity to consider when reconstructing both diet and pottery use from this period. These  
524 changes were not uniform across all of society however. Greater numbers of bones of chickens, and  
525 domestic birds more generally, are found at high status and ecclesiastical sites during the Middle and  
526 Late Anglo-Saxon periods (Poole and Lacey, 2014). Comparison of different sites thus has real potential  
527 to demonstrate differences in dietary intake and consumption practices between different parts of  
528 society. In earlier periods, residue analysis using the approach we describe is essential to understand the  
529 culinary role of poultry and distinguish this from other uses of chickens, such as in ritual practices or for  
530 fighting.

531

532

#### 533 **Conclusion**

534

535 In this study we show that:

536

- 537 ●  $\delta^{13}\text{C}$  values of fatty acids ( $\delta^{13}\text{C}_{\text{FA}}$ ) and collagen ( $\delta^{13}\text{C}_{\text{coll}}$ ) from modern omnivorous animal bone  
538 are correlated and reflect diet
- 539 ●  $\delta^{13}\text{C}_{\text{FA}}$  values in bone reflects the isotopic composition of adipose fat in modern omnivorous  
540 animals and serves as a good proxy. **However, it is reasonable to expect that different animal  
541 tissues (e.g. adipose, bone and bone marrow) were processed in the past and should be  
542 considered.**
- 543 ●  $\delta^{13}\text{C}_{\text{FA}}$  ( $\text{C}_{16:0}$  fatty acid) and  $\delta^{13}\text{C}_{\text{coll}}$  values in archaeological bone are highly correlated. The  
544 former are therefore endogenous and both reflect diet



- 545 ● there is substantial variation in  $\delta^{13}\text{C}_{\text{FA}}$  values between archaeological bone and modern adipose  
546 tissues for monogastric-omnivorous animals reflecting different husbandry practices between  
547 past and present. **Therefore it is highly unlikely that any global  $\delta^{13}\text{C}_{\text{FA}}$  ranges can be derived for  
548 distinguishing monogastric-omnivorous animal fats**
- 549 ● archaeological bone  $\delta^{13}\text{C}_{\text{FA}}$  values from omnivorous animals therefore **complement or provide  
550 an alternative to modern reference fat** for interpreting  $\delta^{13}\text{C}_{\text{FA}}$  values from archaeological ceramic  
551 to determine their use
- 552 ● fatty acids extracted from several vessels from the Anglo-Saxon site of Flixborough have similar  
553  $\delta^{13}\text{C}$  values as those from chicken bones in the same deposits providing the first compelling  
554 evidence of their processing
- 555 ● substantial mixing of different ruminant and monogastric-omnivore products needs to be  
556 resolved in order to determine the importance and nature of poultry processing in the past

557

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565 the manuscript.

566

### 567 **Figure caption**

568

569 Fig. 1. Partial gas chromatogram of adipose and bone lipid extracts from modern chicken tissues (CH-  
570 SP1) and archaeological chicken bone (CHK1).  $\text{C}_{n,x}$  indicates fatty acid with n carbon atoms and x double  
571 bonds; P, phthalates. IS indicates internal standard.

572

573 Fig. 2. Plot of  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids from modern chicken bones and adipose tissue  
574 (Dudd and Evershed, 1998).

575

576 Fig. 3. Plot of  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids from modern chicken bones against their respective  
577 collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values.

578

579 Fig. 4. Plot of  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids from pig, chicken and geese bones against their  
580 respective collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values.

581

582 Fig. 5.  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids from archaeological bones. Data are compared with  
583 ellipses (68% confidence) calculated for fatty acid  $\delta^{13}\text{C}$  values of modern samples from the UK (Dudd and  
584 Evershed, 1998).

585

586 Fig. 6. Collagen  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of archaeological bones.

587  
588 Fig. 7. Partial gas chromatogram of main lipid extracts from Anglo-Saxon potsherds at Flixborough. Fatty  
589 acid  $\delta^{13}\text{C}$  values are indicative of dairy (A), ruminant fat (B), possible chicken fat (C), and goose/pig fat  
590 (D). Partial HT chromatogram of a solvent extract (E).  $\text{C}_{n:x}$  indicates fatty acid with  $n$  carbon atoms and  $x$   
591 double bonds. Phy. - phytanic acid, Alk -  $n$ -alkanes, K - mid-chain ketones, Ch - Cholesterol derivatives.  
592 MAGs are monoacylglycerols of carbon chain length  $x$ , DAGs are diacylglycerols and  $\text{C}_x$  TAGs are  
593 triacylglycerols of carbon chain length  $x$ . IS indicates internal standard.

594  
595 Fig. 8.  $\delta^{13}\text{C}$  values for the  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids extracted from Anglo-Saxon potsherds at Flixborough.  
596 Each data point represents an individual vessel. Data are compared with ellipses (68% confidence)  
597 calculated for the  $\delta^{13}\text{C}$  values of archaeological bone lipids (dotted) and modern adipose and milk (Dudd  
598 and Evershed, 1998). **The theoretical mixing curves illustrate the  $\delta^{13}\text{C}$  values which would result from**  
599 **the mixing of chicken fat with ruminant adipose and milk, goose and pig fat (unfilled circles represent**  
600 **10% increments between mean values).**

601  
602 **Table caption**

603  
604 Table 1.  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids of bone and adipose tissues from modern chicken (CH)  
605 and pig samples.

606  
607 Table 2. The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of bone collagen extracted from modern chicken and pig samples and  
608 the offset with the  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids in bone. Samples extracted with Ultrafiltration  
609 method\*

610  
611 Table 3.  $\delta^{13}\text{C}$  values of  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids of archaeological bones.

612  
613 Table 4. The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of archaeological bone collagen.

614  
615 Table 5. The description of the pottery sherds submitted for analysis and details of the absorbed lipid  
616 residues detected. Composition of lipid extracts. Abbreviations: SFA, saturated fatty acid; MUFA,  
617 monounsaturated fatty acid; DUFA, diunsaturated fatty acid; K, mid-chain ketones; ALK,  $n$ -alkanes; ALC,  
618  $n$ -alcohols; Di, diols; D, diacids; CH, cholesterol, Phy, Phytanic acid; APAA, C16 and C18- $\omega$ -( $o$ -alkylphenyl)  
619 alkanolic acids; MAG, monoacylglycerols; DAG, diacylglycerols; TAG, triacylglycerol. Phases, contexts and  
620 relative age (AD) from Young and Vince (Young and Vince, 2009). Samples trimethylsilylated\*.  
621 Attributions have been made according to the  $\delta^{13}\text{C}_{\text{FA}}$  proximity to the reference ranges shown in Figure 5  
622 and therefore indicate only the most prominent source of animal fat contributing to the contents.

623  
624 **Reference**

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