

# Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney

Schulting, R. J., Vaiglova, P., Crozier, R., & Reimer, P. J. (2017). Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney. *Journal of Archaeological Science Reports*, *11*, 463-470. https://doi.org/10.1016/j.jasrep.2016.12.017

#### Published in:

Journal of Archaeological Science Reports

**Document Version:** Peer reviewed version

**Queen's University Belfast - Research Portal:** Link to publication record in Queen's University Belfast Research Portal

#### Publisher rights © Elsevier Ltd. 2017

This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/,which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

#### General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

#### Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

#### **Open Access**

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: http://go.qub.ac.uk/oa-feedback





Modelled date (BC)



1	Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney
2	
3 ⊿	Rick J. Schulting <sup>**</sup>
4 5	Pella valgiova Bebeeee Crezier <sup>c,d</sup>
5	
7	
8	
9	<sup>a</sup> Research Laboratory for Archaeology and the History of Art, Dyson Perrins Building,
10	South Parks Road, School of Archaeology, University of Oxford, Oxford, OX1 3QY, UK
11	rick.schulting@arch.ox.ac.uk, petra.vaiglova@rlaha.ox.ac.uk
12	
13	<sup>b</sup> Wiener Laboratory for Archaeological Science, American School of Classical Studies
14	Athens, 54 Souidias street, Athens 106 76, Greece
15	
16	Centre for Climate, the Environment & Chronology ("CHRONO), School of Natural
1/ 10	and Built Environment, Queen's University, Beliast, BT7 TNN, UK
10 10	p.j.reimer@qub.ac.uk
20	<sup>d</sup> Archaeological Studies Program, University of the Philippines (Diliman Campus)
21	Quezon City. Manila. 1101. Philippines
22	cccrozier@upd.edu.ph
23	
24	*corresponding author, rick.schulting@arch.ox.ac.uk
25	
26	<b>.</b>
27	Abstract
28	The antiquity of the practice of grazing on and/or foddering with coewood is of interest in
29	terms of understanding animal management practices in porthwest Europe, where
31	provision had to be made for overwintering. Orkney holds a special place in this
32	discussion, since the sheep of North Ronaldsay have been confined to the seashores
33	since the early nineteenth century, and are entirely adapted to a diet consisting mainly
34	of seaweeds. Here, we report the results of stable carbon and nitrogen isotope analysis
35	of twenty-five faunal specimens from the Neolithic chambered tomb of Quanterness,
36	Orkney. Three of the 12 sheep analysed show elevated $\delta^{13}$ C values that can only be
37	explained by the consumption of seaweed. Radiocarbon dates place two of the three
38	animals in the Neolithic, coeval with the use of the monument for burial, while the third
39 40	animal dates to the Chalcolithic/Early Bronze Age. The findings are placed into the
40 41	A disjoint is noted between the results for hone collagen – where seaweed consumption
42	seems to relate to the pre-natal period since all the animals with high $\delta^{13}$ C values are
43	less than ca. three months of age – and previous studies using high-resolution
44	sequential enamel measurements, which suggest a repeated pattern of winter
45	consumption of seaweed in older animals.
46	
47	Key words: stable carbon isotopes; Quanterness chambered tomb; palaeodietary

48 modelling; marine reservoir effect

## 49 **1. Introduction**

The extension of the Neolithic way of life to the fringes of northwest Europe posed new 50 challenges, taking domesticated plants and animals far from their original habitats in the 51 52 Near East. For the latter, the short growing season of browse and graze meant that 53 provision must have been made for the overwintering of domestic stock (Amorosi et al. 54 1998). One resource available year-round along the coasts of northwest Europe is seaweed (e.g., Palmaria palmata, Fucus sp., Laminaria spp.). Historically, there is 55 56 abundant evidence for the use of this resource, usually in dried form, as feed for both 57 cattle and sheep (Chapman and Chapman 1980; Fenton 1978; Hallson 1964; 58 Indergaard and Minsaas 1992; Kelly 1997; Makkar et al. 2016; Martin 1703). Without 59 doubt the most dramatic evidence for this practice comes from North Ronaldsay in Orkney, where a sea-wall was built around the entire island's circumference in the early 60 19<sup>th</sup> century to confine sheep to the seashore for most of the year (Fenton 1978; 61 62 Hansen et al. 2003). Thus the question arises as to when this practice first emerged. The fact that consumption of seaweed leaves a distinct signal in the animals' stable 63 carbon ( $\delta^{13}$ C) and oxygen ( $\delta^{18}$ O) isotope signatures – effectively making them appear 64 65 isotopically similar to marine organisms (Ambers 1990) – provides the opportunity to explore this guestion with zooarchaeological remains. A small number of cases of 66 67 sheep consuming seaweed in Orkney during the Neolithic have been previously identified using this method (Balasse et al. 2005; 2006; 2009; Balasse and Tresset 68 69 2009; Schulting et al. 2004; Schulting and Richards 2009). Here, we provide new evidence from the results of a programme of stable carbon ( $\delta^{13}$ C) and nitrogen ( $\delta^{15}$ N) 70 isotope analysis and accelerator mass spectrometry (AMS) radiocarbon dating of a 71 72 faunal assemblage from the Middle-Late Neolithic chambered tomb of Quanterness. 73 Mainland, Orkney.

74

#### 75 **2. Overview of stable carbon and nitrogen isotope analysis**

Measurements of bone collagen stable carbon ( $\delta^{13}$ C) and nitrogen ( $\delta^{15}$ N) values are frequently used in archaeology to investigate the major sources of dietary protein (Ambrose and Norr 1993; Lee-Thorp 2008). The values obtained via isotope ratio mass spectrometry (IRMS) provide a relatively long-term average of primarily protein intake, though the exact length of time represented will depend on the rate of remodeling of the 81 sampled bone, but will always be more rapid in young, growing animals. The ratios of stable C and N isotopes incorporated into animal tissues are driven by the isotopic 82 composition of major dietary sources. Marine organisms, including seaweed, shellfish, 83 fish and sea mammals, are enriched in <sup>13</sup>C relative to <sup>12</sup>C due to the fact that the ocean 84 85 serves as a sink for the heavier isotope (Boutton 1991; Sharp 2007). As a result, 86 organisms obtaining a significant proportion of their dietary protein from marine foods will exhibit higher  $\delta^{13}$ C values (ca. -12 ± 1‰) than those subsisting solely on C<sub>3</sub> 87 terrestrial foods, which provide lower values (ca. -21 ± 1‰) for bone collagen (Richards 88 89 and Hedges 1999). The consumption of C<sub>4</sub> plants such as maize and millet would result 90 in even higher bone collagen values than the consumption of marine foods, but as no 91 such plants were found in northwest Europe during the study period, they need not be 92 considered here.

93

94 Stable nitrogen isotope ratios are used to investigate trophic levels. There is a variable 95 but broadly predictable increase of ca. 3–5‰ between dietary item and consumer tissue for each step in the food chain (Ambrose 2000; Caut et al. 2009; Hedges and Reynard 96 97 2007; Schoeninger and DeNiro 1984). This range is generally cited for human consumers, and may be towards its lower end for most herbivores. The comparable 98 99 effect in  $\delta^{13}$ C is considerably smaller, about 1‰ (Bocherens and Drucker 2003; Lee-Thorp *et al.* 1989). The ocean is also enriched in <sup>15</sup>N relative to atmospheric N<sub>2</sub> (defined 100 101 as 0‰), the latter serving as the ultimate source of nitrogen for terrestrial plants (Peterson and Fry 1987). Thus marine plants will generally have higher  $\delta^{15}$ N values 102 103 than most temperate terrestrial plants under natural conditions (i.e., in the absence of 104 anthropogenic input). Furthermore, because marine food webs are considerably more 105 complex (i.e., involve more steps) than terrestrial mammalian food webs, there is scope for much greater trophic level enrichment, such that high-level marine carnivores can 106 exhibit collagen  $\delta^{15}$ N values of +16‰ or more (Schoeninger and DeNiro 1984). Other 107 factors can also result in <sup>15</sup>N enrichment, most notably aridity, but this can safely be 108 109 excluded from discussions pertaining to Orkney.

110

#### 111 **3. Materials and Methods**

112 The Quanterness chambered tomb is located near the east-central coast of Mainland 113 Orkney, northern Scotland (Figure 1). It serves as one of the two type-sites for the 114 Quanterness-Quoyness type of passage tomb (also known as the Maes-Howe type). 115 Excavated by Colin Renfrew in the 1970s (Renfrew 1979), the site yielded a large 116 human skeletal assemblage (Crozier 2012), as well as ceramic, lithic and faunal 117 remains. A recent dating programme focusing on the human remains placed the use of 118 the monument for burial in the second half of the fourth millennium BC, continuing into 119 the first guarter of the third millennium (Schulting et al. 2010). The original dating 120 programme also identified one example (Pit C) of deposition of human remains in the 121 third guarter of the third millennium BC (Renfrew 1979).

122

123 For this study, twenty-five faunal bone samples from the Quanterness assemblage were selected for  $\delta^{13}$ C and  $\delta^{15}$ N analysis. The samples included domestic sheep (*Ovis aries,* 124 n=14, all left humeri; 1 foetal, 8 juveniles, 1 adolescent, 4 adults), domestic cattle (Bos 125 126 *Taurus*, n=6, pelvae and ribs; 3 perinatal, 3 adults), domestic pig (*Sus scrofa*, n=3, 127 ulnae; 1 infant, 1 juvenile, 1 adult), dog (Canis domesticus, n=1, right femur; adult) and 128 red deer (Cervus elaphus, n=1, left humerus; adolescent). The identification of the 129 sampled humeri as sheep rather than goat is not based on their morphology (though 130 this is possible - see Zeder and Lapham 2010), but rather on the scarcity of identified 131 goat remains in Neolithic and Bronze Age Orkney overall. They will be referred to here 132 as 'sheep': while there is a possibility that some are goat, this does not impact on the 133 larger discussion.

134

135 Figure 1. Map of Orkney showing locations mentioned in the text.

136

The sheep/goats (henceforth 'sheep') were aged using standards in Moran and O'Connor (1994) and Popkin *et al.* (2012). One complete but very small humerus (greatest length = 35.2mm) is from a foetal lamb far from full term (McDonald *et al.* 1977). Six animals are aged between birth and ca. 3 months based on the lengths of (66-70mm) for three complete humeri, and a comparison of maximum breadth of these specimens against the three incomplete elements. Three further humeri were in the process of fusing distally, placing them at  $\geq$ 6 months. Finally, four animals are classed 144 as adults based primarily on their size, confirmed by the fully fused proximal humerus in145 the single complete specimen (>36 months).

146

147 Collagen was extracted from the samples following a modified Longin procedure

- 148 (Longin 1971; Richards and Hedges 1999). Measurements were made in duplicate on a
- 149 SerCon 'Callisto' continuous flow IRMS coupled to an elemental analyser at the
- 150 Research Laboratory for Archaeology and the History of Art, University of Oxford. An
- alanine standard was used to correct for machine drift and calculate the measurement
- 152 precision (1 $\sigma$ ) at 0.2% for  $\delta^{13}$ C and ±0.3% for  $\delta^{15}$ N.  $\delta^{13}$ C and  $\delta^{15}$ N are reported as per
- 153 mil (‰) relative to the international standards VPDB and AIR, respectively. C:N values
- are reported as atomic ratios and serve as a check on collagen preservation (cf DeNiro155 1985).
- 156

AMS radiocarbon dating was undertaken at the <sup>14</sup>CHRONO laboratory at Queen's 157 University Belfast. The sample <sup>14</sup>C/<sup>12</sup>C ratio was background corrected and normalised 158 159 to the HOXII standard (SRM 4990C; National Institute of Standards and Technology) 160 and corrected for isotopic fractionation using the AMS-measured  $\delta^{13}$ C to account for both natural and machine fractionation. The <sup>14</sup>C age and associated error were 161 162 calculated using the Libby half-life (5568 years) following the conventions of Stuiver and 163 Polach (1977). Nine samples were selected, targeting all the domestic species 164 represented at Quanterness, as well as one of the small number of red deer elements. The main focus, however, was on sheep, since firstly, this taxon dominates the faunal 165 assemblage (Clutton-Brock 1979), and secondly, the  $\delta^{13}$ C results highlighted 166 167 considerable variability, and the sources of this variation were of particular interest. All 168 calibrated dates are reported at 95.4% confidence.

169

## 170 **3. Results**

171 The faunal stable isotope results from Quanterness are provided in Table 1 and plotted

in Figure 2. All samples passed collagen quality criteria including collagen yields and

173 C:N ratios (Ambrose 1990; DeNiro 1985; van Klinken 1999).

Cat. No.	Species, Latin name	Species	Element	Age	$\delta^{I3}C$	$\delta^{15}N$	C:N
3074.22	Ovis aries	sheep	L humerus	foetal	-20.8	8.3	3.3

2491.04	Ovis aries	sheep	L humerus	0-3 mon	-17.8	8.3	3.3
4084.48	Ovis aries	sheep	L humerus	0-3 mon	-19.8	7.5	3.3
146.07	Ovis aries	sheep	L humerus	0-3 mon	-18.6	8.7	3.3
4084.2	Ovis aries	sheep	L humerus	0-3 mon	-16.9	9.6	3.3
3072.03	Ovis aries	sheep	L humerus	0-3 mon	-19.9	8.7	3.2
4029.07	Ovis aries	sheep	L humerus	0-3 mon	-22.2	9.6	3.3
4081.80	Ovis aries	sheep	L humerus	ca. 6 mon	-22.3	9.6	3.2
2416.03	Ovis aries	sheep	L humerus	> 6 mon	-21.2	5.9	3.3
4570.02	Ovis aries	sheep	L humerus	> 6 mon	-21.2	5.6	3.3
1328.02	Ovis aries	sheep	L humerus	adult	-20.4	5.8	3.3
249.11	Ovis aries	sheep	L humerus	adult	-20.7	6.9	3.3
2584.02	Ovis aries	sheep	L humerus	adult	-21.0	5.5	3.3
2361	Ovis aries	sheep	L humerus	adult	-22.0	8.5	3.2
803.2	Bos taurus	cattle	innominate	perinatal	-21.7	6.6	3.4
1258.03	Bos taurus	cattle	innominate	perinatal	-21.7	5.2	3.3
284	Bos taurus	cattle	innominate	perinatal	-21.0	6.4	3.3
4610	Bos taurus	cattle	rib	adult	-21.4	5.4	3.2
90.01	Bos taurus	cattle	rib	adult	-21.5	5.1	3.3
1050	Bos taurus	cattle	rib	adult	-21.6	5.4	3.3
4500.04?	Sus domesticus	pig	ulna	juvenile	-22.1	6.7	3.3
5004.11	Sus domesticus	pig	ulna	adult	-20.4	8.2	3.2
4580.16	Sus domesticus	pig	ulna	infant	-21.8	8.3	3.3
4526.01	Canis domesticus	dog	R femur	adult	-20.6	9.1	3.2
1345.04	Cervus elaphus	red deer	L humerus	adol	-20.9	5.3	3.3

177

176

Table 1. Quanterness fauna sample details and results of  $\delta^{13}$ C and  $\delta^{15}$ N analysis.

The six cattle values cluster tightly at -21.5  $\pm$  0.3‰ and 5.7  $\pm$  0.6‰ for  $\delta^{13}$ C and  $\delta^{15}$ N 178 179 values, respectively. The single red deer value is comparable (-20.9‰, 5.3‰). The three pigs analysed exhibit similar  $\delta^{13}$ C values (-21.4 ± 0.9‰) but are significantly 180 elevated above cattle and deer in  $\delta^{15}N$  (7.7 ± 0.9‰), reflecting their more omnivorous 181 diets. The single domestic dog in the study yielded values of -20.6‰ and 9.1‰ for  $\delta^{13}$ C 182 183 and  $\delta^{15}$ N, respectively.

184

The range of  $\delta^{13}$ C values for sheep (-22.3 to -16.9‰) is considerably wider than that 185 seen in the other species. However, as noted below, the lowest values may date to the 186 187 medieval period. More interesting are three of the juvenile sheep aged 0-3 months occupying the higher end of the range: including the other two animals in this age class 188 (excluding the lowest value), this group averages -18.6  $\pm$  1.3% for  $\delta^{13}$ C and 8.6  $\pm$  0.8% 189 for  $\delta^{15}$ N values, compared to -20.9 ± 0.35‰ and 5.9 ± 0.6‰ for the five animals older 190 191 than ca. six months (i.e., with fused distal epiphyses). The foetal sample is indistinguishable from the adults in its  $\delta^{13}$ C value (-20.8%), as would be expected, but 192 has a high  $\delta^{15}$ N value (8.3‰), considerably higher than seen in the adult animals. While 193

- this would be unexpected in humans, it has been previously observed in sheep, and
- 195 may relate to differing placental systems (Balasse 1999: Appendix II, and pers. comm.).
- As expected, the young lambs (0-3 months) are also enriched in <sup>15</sup>N compared to the
- 197 older lambs and adult sheep (Table 2).
- 198
- 199 Figure 2. Plot of faunal and human  $\delta^{13}$ C and  $\delta^{15}$ N results from Quanterness (human
- 200 data from Schulting *et al.* 2010).
- 201

Species		$\delta^{I3}C$	±	$\delta^{15}N$	±	п
shee	р					
	all	-20.3	1.6	7.8	1.5	14
	foetal	-20.8	-	8.3	-	1
	0-3 mon	-18.6	1.3	8.6	0.8	5
	> 6 mon	-20.9	0.3	5.9	0.6	5
	medieval?	-22.2	0.2	9.2	0.6	3
cattle		-21.5	0.3	5.7	0.6	6
	all	-21.5	0.4	5.7	0.6	6
	perinatal	-21.5	0.4	6.1	0.8	3
	adult	-21.5	0.1	5.3	0.2	3
pig		-21.4	0.9	7.7	0.9	3
dog		-20.6	-	9.1	-	1
red deer		-20.9	-	5.3	-	1

- Table 2. Summary statistics for Quanterness faunal  $\delta^{13}$ C and  $\delta^{15}$ N measurements. The
- sheep identified as likely of medieval date (see Table 3) are included in the total but
- 205 treated separately in the age categories.
- 206
- 207

Cat no.	Species	Age	Lab code	<sup>14</sup> C vrs	±	cal BC	(95,4%)	$\delta^{13}C$	$\delta^{15}N$	C:N	%mai
4084.2	Ovis Aries	0-3 mon	UBA-18429	4499	32	3084	2866	-16.9	9.6	3.3	46
146.07	Ovis Aries	0-3 mon	UBA-18428	4197	34	2864	2495	-18.6	8.7	3.3	27
2491.04	Ovis Aries	0-3 mon	UBA-18426	3855	29	2286	1981	-17.8	8.3	3.3	36
249.11	Ovis Aries	adult	UBA-18425	3367	31	1632	1427	-20.7	6.9	3.3	3
4029.07	Ovis Aries	0-3 mon	UBA-18427	908	25	AD 11	68-1300	-22.2	9.6	3.3	0
4580.16	Sus domesticus	infant	UBA-18432	4302	37	3014	2880	-21.8	8.3	3.3	0
1345.04	Cervus elaphus	adol.	UBA-18431	3785	28	2196	1939	-20.9	5.3	3.3	1
1258.03	Bos taurus	perinatal	UBA-18433	3649	24	2009	1755	-21.7	5.2	3.3	0
	Canis										
4526.01	domesticus	adult	UBA-18430	3466	24	1743	1535	-20.6	9.1	3.2	4

- 209 Table 3. Results of <sup>14</sup>C dating. Mixed marine-terrestrial curves are used for the three
- young sheep with significantly elevated  $\delta^{13}$ C values (Reimer *et al.* 2013).
- 211
- The radiocarbon dating results range widely, from 4499  $\pm$  32 BP (UBA-18429) to 908  $\pm$
- 213 25 BP (UBA-18427) (Table 3). Calibration of the dates for three young lambs including
- the earliest result in the series is complicated by their elevated  $\delta^{13}$ C values suggesting

215 that they consumed significant amounts of marine foods. The use of a mixed marine/terrestrial curve is therefore required, with '%marine' being calculated using a 216 217 simple linear extrapolation between marine and terrestrial bone collagen endmembers 218 of -12‰ and -21‰, respectively (Barrett and Richards 2004; Richards and Hedges 219 1999; Schulting and Richards 2009) (Table 2). The validity of these endmembers has 220 been repeatedly confirmed on studies of archaeological marine and terrestrial fauna 221 from western and northern Scotland (Charlton et al. 2016; Montgomery et al. 2013; 222 Mulville et al. 2009; 2013; Richards et al. 2006). The estimate is assumed to have an 223 uncertainty of  $\pm 10\%$ , included in the model (OxCal 4.2). A local  $\Delta R$  of 48  $\pm$  47 years has 224 been used, based on the four nearest datapoints in Calib's Marine Reservoir 225 Corrections Database (http://calib.qub.ac.uk/marine/). No correction has been applied 226 for cases in which the estimated '% marine' is less than 5%, since the contribution of any 227 marine protein is uncertain at best.

228

229 Once calibrated, three results fall within the early to mid-third millennium cal BC, 230 conventionally designated as Late Neolithic in a British context, although the first 231 century or so of the third millennium is probably better understood as culturally 'Middle 232 Neolithic' in the sense that passage tombs still featured prominently on the mortuary 233 landscape (Schulting et al. 2010). Three results fall within the late third to early second 234 millennium, towards the end of the Chalcolithic in one case and within the Early Bronze 235 Age in the other two. Two results lie within the mid- to late second millennium, on the 236 border between the Early and Middle Bronze Age. Finally, the latest determination 237 within the group is clearly an outlier, falling within the medieval or late Norse period, cal 238 AD 1168–1300. This particular sample, a young lamb, was selected as one of three showing unusually low  $\delta^{13}$ C values, of -22.0% or less (Table 1). On this basis we 239 240 suspect, though cannot demonstrate, that all three samples may be medieval in date. 241 Figure 3. OxCal 4.2 (Bronk Ramsev 2013) plot of calibrated faunal dates from 242

243 244

# 245 **4. Discussion**

246 4.1 Implications for animal management

Quanterness (excluding UBA-18427, 908 ± 25 BP).

Significantly elevated  $\delta^{13}$ C values for three of the 14 sheep analysed from Quanterness 247 indicate the consumption of seaweed (for a summary of  $\delta^{13}$ C measurements made on 248 249 seaweeds from across the UK, see Balasse et al. 2005: table 1). There are no other 250 possibilities for enriched <sup>13</sup>C resources on the archipelago at this time, nor is there any 251 issue with the identification of the skeletal elements (left humeri) selected for analysis: 252 they are definitely ovicaprids. Based on the linear extrapolation used to correct their 253 radiocarbon dates for the marine reservoir effect, it is estimated that these three lambs 254 obtained between ca. 27% and 46% of their dietary protein from seaweeds, albeit 255 indirectly since they would be too young to be grazing. The results join previous 256 research that has identified a small number of sheep from prehistoric sites on Orkney with elevated  $\delta^{13}$ C values similarly indicating the consumption of seaweeds. Two 257 258 neonatal lambs from Holm of Papa Westray North (HPWN) are represented by 259 measurements on bone collagen, initially identified through radiocarbon dating (Bronk 260 Ramsey et al. 2002; Schulting et al. 2004), with one sample re-analysed specifically for 261 palaeodietary reconstruction (Schulting and Richards 2009). One of these neonates 262 vielded extremely elevated  $\delta^{13}$ C and  $\delta^{15}$ N values of -12.8‰ and 12.6‰, respectively. 263 Essentially, this can be considered a 100% marine diet. However, given that this animal 264 did not survive past infancy, this diet may have been in extremis on the part of its 265 mother rather than the result of an intentional management strategy. One previously 266 suggested possibility is that this sheep was part of a feral flock - or even just a few 267 animals – abandoned on the islet, though this in itself may be seen as part of a 268 management strategy (Balasse and Tresset 2009; Schulting and Richards 2009: 72). 269

The animals showing high  $\delta^{13}$ C values also tend to be elevated in  $\delta^{15}$ N. While this may 270 271 partly reflect the predictable enrichment caused by the nursing effect (Jenkins et al. 2001), such high values must be related to the considerably <sup>15</sup>N-enriched content of 272 seaweeds compared to grasses (Caumette et al. 2007). This is supported by the strong 273 positive correlation between  $\delta^{13}$ C and  $\delta^{15}$ N values ( $r^2 = 0.767$ , p < 0.001) seen in the 274 275 Quanterness sheep (excluding the three cases thought to be medieval). Extending this 276 analysis to include the sheep from HPWN and other Neolithic and Bronze Age sites on Orkney (Jones and Mulville 2016) reduces the strength of correlation ( $r^2 = 0.609$ , p < 100277 278 0.001) but only because of the greater scatter at the low end of the scale for both

279 elements (Figure 4). It is worth noting that, while the sheep/goat data presented by Jones and Mulville (2016: table 2) do not include any definite examples of seaweed 280 consumption (average -20.8  $\pm$  0.6%, maximum -19.7%, n = 26), three animals do have 281 values above -20%. Moreover, there is a slight but significant positive correlation 282 between  $\delta^{13}$ C and  $\delta^{15}$ N values ( $r^2 = 0.127$ , p = 0.045), which may plausibly reflect some 283 marine influence (cf. Richards and Hedges 1999). As Jones and Mulville (2012: 670; 284 285 see also Jones et al. 2012) note, it is possible that this is the result of foreshore grazing on terrestrial plants enriched in <sup>13</sup>C and <sup>15</sup>N due to salinity effects (Heaton 1987; Britton 286 287 et al. 2008), rather than the consumption of seaweed. However, this cannot account for 288 the more elevated values seen in the young animals from Quanterness and HPWN. The absence of comparably elevated  $\delta^{13}$ C values in the larger number of samples analysed 289 290 by Jones and Mulville can be explained by their decision to focus only on mature 291 animals, to avoid complications introduced by nursing effects (2012: 668). While entirely 292 understandable, this creates ambiguity in the interpretation of the adult values, and 293 could mask periods of significant consumption of marine resources.

294

Figure 4. Plot of bone collagen  $\delta^{13}$ C and  $\delta^{15}$ N measurements on sheep/goat from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting and Richards 2009). The three squares identify low values thought to be medieval intrusions, and are not included in the regression.

300 Orcadian Neolithic and Bronze Age cattle, by contrast, show no correlation between  $\delta^{13}$ C and  $\delta^{15}$ N values ( $r^2 = 0.059$ , p = 0.158) (Figure 5). This is consistent with results 301 302 from tooth enamel carbonate studies on cattle that have found no evidence for seaweed 303 consumption (Balasse et al. 2006; Towers et al. 2016), despite their social and 304 economic importance on Orkney from the Neolithic onwards. This may reflect the more 305 adaptable gut physiology of sheep, in particular their tolerance of the high levels of 306 arsenic found in seaweeds (Caumette et al. 2007; Feldman et al. 2000). However, this 307 cannot be the entire explanation, since supplementing cattle fodder with seaweed is 308 well attested historically (Hallson 1964; Makkar et al. 2016; Martin 1703). Perhaps the 309 greater value of cattle - and hence greater investment in them - meant that the bulk of the winter hay and chaff from C<sub>3</sub> plants was reserved for them. 310

Figure 5. Plot of bone collagen  $\delta^{13}$ C and  $\delta^{15}$ N measurements of humans and fauna from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting et al. 2010; Schulting and Richards 2009).

315

A number of other examples interpreted as indicative of seaweed consumption in 316 Neolithic Orkney derive from sequential  $\delta^{13}$ C measurements of tooth enamel from Point 317 of Cott and HPWN, dating to ca. 3000 cal BC (Barber 1997; Ritchie 2009) and hence 318 319 being contemporary with the earliest results from Quanterness. This method has the 320 distinct advantage of providing resolution on an intra-annual seasonal level through comparison with accompanying  $\delta^{18}$ O measurements (Balasse *et al.* 2005; 2006; 2009; 321 322 Balasse and Tresset 2009). At Point of Cott, one of three sheep second molars analysed presented a peak indicating a significantly <sup>13</sup>C-enriched diet for part of the 323 tooth mineralization period (Balasse et al. 2009). By contrast, all 12 sheep molars (M2s 324 325 and M3s, representing the first and second years of life, respectively - Milhaud and Nezit 1991) analysed from HPWN recorded peaks in  $\delta^{13}$ C values during the colder 326 season as represented by lower  $\delta^{18}$ O values, though not as low as would be expected 327 for animals drinking from terrestrial water sources in the winter (Figure 6a) (Balasse et 328 329 al. 2006; Balasse and Tresset 2009). Balasse and colleagues reasonably inferred from 330 this that the HPWN sheep consumed fresh seaweed on the seashore (and ingested the 331 oceanic water contained therein), rather than being foddered in the winter with dried seaweed collected specifically for this purpose (a practice for which there are historical 332 references). The high enamel  $\delta^{13}$ C values suggest that the winter diet consisted of 333 334 approximately 45-70% seaweed (Balasse et al. 2006: 173), so that the animals must 335 still have had access to terrestrial vegetation. By contrast, none of the 11 sheep molars 336 analysed from the nearby settlement of Knap of Howar, dating to a few centuries earlier - to ca. 3600 cal BC – show enriched  $\delta^{13}$ C values (Figure 6b). As Balasse *et al.* (2006) 337 338 note, this could place the origins of the practice of seaweed foddering on Orkney 339 towards the end of the fourth millennium BC. The Quanterness data support the 340 consumption of seaweed by sheep dating to the same time period, but in the absence of earlier animals from the site cannot shed further light on this issue. 341 342

Figure 6. Plot of sequential enamel  $\delta^{13}$ C and  $\delta^{18}$ O measurements on sheep third molars from a) Holm of Papa Westray North, and b) Knap of Howar (Balasse and Tresset 2009).

347 The modern and historically attested lambing season on Orkney takes place relatively late, from late April to May/June (Balasse et al. 2006). Given a five month gestation 348 349 period, the foetus would be developing *in utero* from November to birth from late April. 350 The scarcity of grass over the winter months would make this period suited to the use of 351 seaweed as alternative fodder. Assuming that this pattern is broadly comparable to that 352 in the mid-Holocene (and there is no reason to think otherwise, given the absence of 353 significant climate change in the intervening period), then lambing would most likely 354 take place on the newly revitalised spring pastures. This also seems more probable 355 from the point of view of the safety of the newborn lambs, which might be susceptible to 356 being swept out to sea in the intertidal zone. Indeed, this is the current and historically 357 documented practice on North Ronaldsay, with females being moved from the shore 358 onto inland pastures for lambing (Fenton 1978; Hansen et al. 2003).

359

360 The proportion of seaweed in the diet of the animals at HPWN suggested by the enamel  $\delta^{13}$ C values (45-70%) would be expected to result in bone collagen values for the 361 362 newborn lambs of ca. -14.7‰ to -17.0‰. While we cannot assume similar animal 363 management practices between the two sites, it can be noted that, while the observed 364 values for lambs in the 0-3 month age class at Quanterness do retain a 'marine 365 influence', they are lower than this, ranging from -16.9% to -19.9%. But, following on 366 from the above discussion, newborn lambs would be nursing on milk produced by ewes 367 feeding on new grass. Because of the rapid growth seen in the skeletons at this age, their bone collagen  $\delta^{13}$ C values would change relatively rapidly, so that after three 368 369 months they might very well fall within the observed range. The few older lambs that 370 have been measured show no influence of seaweed. It is surprising that both they and 371 the adult animals show so little input into their bone collagen of the winters spent, by at 372 least some animals, during the first and second years of life consuming significant 373 amounts of seaweed, as indicated by the sequential enamel measurements on second 374 and third molars from Point of Cott and HPWN. While we cannot guarantee that any of 375 the same animals were measured in the enamel and the bone collagen studies, given 376 that all 12 molars analysed at HPWN showed seasonal consumption of seaweed, we 377 would expect to find more evidence of this in the collagen of older animals, though

admittedly there are only two measurements on adult sheep currently available from the
site (Schulting and Richards 2009). That it was not detected at Knap of Howar is not
surprising, since the enamel results did not find any evidence for the practice there.

381

382 By contrast, bone collagen of modern adult sheep on North Ronaldsay, confined to the seashore for most of the year, have the expected high  $\delta^{13}$ C values averaging ca. -13‰ 383 (Ambers 1990). While the adolescent and adult sheep from Quanterness do have 384 significantly higher average  $\delta^{13}$ C values than the cattle from the site (-20.9% vs. -385 386 21.5‰, Student's t-test, t = 3.18, p = 0.011), the difference is only 0.6‰. This is hard to 387 reconcile, though of course the same animals are not being measured in the enamel 388 and collagen studies, nor indeed are they from the same site, though they are 389 approximately contemporary and in relatively close proximity to one another. (That 390 measurements on enamel reflect whole diet while collagen measurements are biased 391 towards dietary protein (Ambrose and Norr 1993) should not be an issue here, since 392 seaweeds and grasses appear to have similar protein content and digestibility (Hansen 393 et al. 1991)). Statistically significant differences of a similar order were identified between sheep/goat and cattle  $\delta^{13}$ C values by Jones and Mulville (2016: 668-669) for 394 395 Neolithic, Bronze Age and Iron Age Orkney, as well as for the Bronze Age of the 396 Western Isles (though not the Neolithic or the Iron Age). However, as noted above, this 397 could relate in part to coastal grazing rather than episodic high seaweed consumption. Sequential enamel  $\delta^{13}$ C analyses of sheep and cattle from the Iron Age and Norse 398 399 periods in Orkney have found no evidence for seaweed foddering (Mainland et al. 400 2016). Ambers (1990) also found no evidence for the practice in prehistoric Orkney, in a study using  $\delta^{13}$ C measurements on bone collagen. 401

402

Given that only very young animals show a distinct 'marine'  $\delta^{13}$ C signal, it is possible that foddering pregnant ewes with seaweed was in fact a last resort when terrestrial resources failed, so that young animals born when their mothers had been on this diet were more likely to die, and hence retain elevated  $\delta^{13}$ C values in their bone collagen. This is reminiscent of a recent study of sequential human dentine isotope measurements from a Neolithic site on the small island of West Voe, Shetland, showing that those individuals with periodic high use of marine resources were more likely to die young (Montgomery *et al.* 2013). In both cases the burial assemblage is intrinsically
biased by differential survivorship – the classic 'osteological paradox' (Wood *et al.*1992).

413

## 414 4.2 Implications for Neolithic human diet

415 The evidence for seaweed consumption by pregnant ewes, seen most clearly in 416 newborn lambs, raises questions regarding their impact on human diets. Essentially, a 417 'marine' isotopic signal could be introduced through the consumption of a terrestrial 418 mammal. As discussed in Schulting and Richards (2009), this is an alternative 419 explanation to the direct exploitation of marine resources for the slight elevation in the 420  $\delta^{13}$ C values observed in human bone collagen from the chambered tomb of HPWN. 421 However, this slight elevation was being considered in comparison with the human 422 results from Quanterness, where there seems to be no clearly detectable impact on  $\delta^{13}$ C values of the use of marine resources (-20.6 ± 0.3‰), whether direct or indirect 423 424 (Figure 2). Following the discussion above, this is perhaps not surprising. Only a small 425 number of very young lambs show significantly enriched carbon and nitrogen isotope 426 values. Once on grass, which likely was the case from birth, their flesh values would very quickly become depleted in <sup>13</sup>C, reflecting this dietary change. The bone collagen 427 428 of adult sheep appears to show surprisingly little impact of seaweed consumption, 429 though interpretation is complicated by the bone and tooth enamel analyses being 430 conducted on different animals.

431

432 Another finding to emerge from this study is that the use of direct radiocarbon dating of 433 at least a sample of faunal remains is essential in those cases where the 434 contemporaneity of the faunal assemblage cannot be securely assigned to a phase on 435 archaeological/stratigraphic grounds. This is highlighted here by the fact that only three 436 of the nine determinations returned results coeval with the use of the chambered tomb 437 for burial in the Late Neolithic. Despite the presence of intrusive fauna, it is interesting to note that the early dates include one of the three pigs represented in the study. Pigs are 438 439 relatively rare in Orcadian Neolithic faunal assemblages, and this can be explained by 440 the limited availability of natural habitat suited to their foraging preferences (i.e., 441 woodland). Hence, they would likely need to be supplied with food at least some of

which would be suitable for humans, and would thus be in competition (McCormick and
Buckland 2003: 91; Schulting 2013). A small number of pigs may have been fed on
domestic refuse and crop waste. Pigs can also be fed marine foods (seaweed, shellfish,
fish), but, surprisingly, there is no isotopic evidence for this in Orcadian prehistory. It is
not until the Iron Age that we see convincing evidence for this practice, not in Orkney,
but in the Western Isles (Jones and Mulville 2016: figure 13).

448

449 Three faunal samples can be placed within the Chalcolithic/Early Bronze Age, while 450 another two lie at the Early-Middle Bronze Age border. This chronology is considerably 451 more extended than that for the human remains (Schulting et al. 2010). What is less 452 clear is the nature of the deposition of the faunal remains post-dating the use of the 453 tomb for burial. The lack of other finds (e.g., pottery) dating to the Bronze Age suggests 454 that the deposition may not have been intentional, or at least not ritual, but rather that 455 animals sought shelter in the monument and died there naturally, or were disposed of 456 there by Bronze Age farmers. A re-examination of the fauna for butchery marks might 457 help in choosing between these alternatives, although the mixed nature of the deposits 458 means that an extensive programme of radiocabron dating would be required to identify 459 the Bronze Age component. Finally, one juvenile sheep dates to the medieval period, 460 known as the late Norse period on Orkney. The latter is particularly significant, since it is one of a group of three animals with notably lower than average  $\delta^{13}$ C values at the site. 461 462 Assuming that the other two animals are also later intrusions, it is clear that using these 463 results for formal palaeodietary modelling of the human isotopic results could be highly 464 misleading. If it is confirmed that all three are late, a question is raised over why they should be depleted in <sup>13</sup>C during this period. 465

466

## 467 **5. Conclusions**

The faunal  $\delta^{13}$ C and  $\delta^{15}$ N data from Quanterness provide further evidence for the consumption of seaweeds, probably by pregnant ewes, on Orkney from the late fourth millennium BC, with additional cases in both the early and late third millennium,

471 extending the temporal range of this practice into the Chalcolithic. However, the extent

- to which this was part of an ongoing, intentional management strategy remains unclear.
- 473 An alternative scenario is that the use of seaweed was a fallback strategy in years

where insufficient terrestrial grasses were available to last the winter. Only a very minimal increase in  $\delta^{13}$ C values can be found in the bone collagen of older lambs and adult animals, so that little impact on human diets would be expected, consistent with what has been observed in the previously published human results from Quanterness (Schulting et al. 2010).

479

480 It is clear that further research is required to better understand the origins and 481 implications of the practice of seaweed foddering in northern Europe. Enamel studies 482 have indicated recurrent substantial consumption of seaweed in the winter by 483 adolescent and adult sheep, yet the impact on bone collagen is minimal. However, 484 these studies have rarely been joined up, and have been carried out on different 485 individuals often from different sites. Clearly there is scope for a more coordinated 486 effort, which could also include dental microwear analysis (e.g., Mainland et al. 2016), 487 which has been shown to be capable of distinguishing between seaweed and grass grazing sheep (Mainland 2000). There is currently an impression that the practice did 488 489 not continue into later prehistory, suggesting that perhaps it was not particularly 490 successful as a management strategy, at least until revived in the nineteenth century on 491 North Ronaldsay. It should not be assumed that once a new farming practice appears, it 492 will continue to be used thereafter. Future research will need to focus on immature 493 animals and sequential sampling of both enamel and dentine.

494

## 495 Acknowledgements

496 Many thanks to Alison Sheridan and the National Museums Scotland for permission to 497 sample the Quanterness fauna and to Richard Sabin of the Natural History Museum, 498 London, for facilitating access to the collection, which was in temporary storage there. 499 Thanks also to Marie Balasse and an anonymous referee for their very useful feedback, 500 and to Marie Balasse for permission to cite her doctoral thesis and to reproduce a graph 501 of her stable isotope results. The wonderful photograph of a seaweed-eating sheep 502 from North Ronaldway in the graphical abstract is courtesy of the Orkney Sheep 503 Foundation. The research was supported by the Research Laboratory for Archaeology and the History of Art, University of Oxford, and by the <sup>14</sup>CHRONO laboratory, Queen's 504

- 505 University Belfast. The authors did not receive any specific grant from funding agencies
- 506 in the public, commercial, or not-for-profit sectors.

## 507 **References**

508

Ambers, J.C., 1990. Identification of the use of marine plant material as animal fodder by stable isotope ratios, PACT 29, 251-258.

511

512 Ambrose, S.H., 1990. Preparation and characterization of bone and tooth collagen for 513 isotopic analysis, J. Archaeol. Sci. 17, 431-451.

514

Ambrose, S.H., Norr, L., 1993. Experimental evidence for the relationship of the carbon
isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate,
in: Lambert, J.B., Grupe, G. (Eds.), Prehistoric Human Bone: Archaeology at the

- 518 Molecular Level, Springer-Verlag, New York, pp. 1-37.
- 519
- 520 Amorosi, T., Buckland, P., Edwards, K., Mainland, I., McGovern, T., Sadler, J.,
- 521 Skidmore, P., 1998. They did not live by grass alone: the politics and palaeoecology of 522 animal fodder in the North Atlantic region, Env. Archaeol. 1, 41–54.
- 523
- Balasse, M. 1999. De l'exploitation du lait au Néolithique moyen, en Europe tempérée.
  Examen des modalités de sevrage des bovins, par l'analyse isotopique des ossements
  archéologiques. Thèse de doctorat de l'Université Paris 6, Mémoires des Sciences de la
  Terre 99-26, Paris.
- 528

Balasse, M., Mainland, I.L., Richards, M.P., 2009. Stable isotope evidence for seasonal
consumption of marine seaweed by modern and archaeological sheep in the Orkney
archipelago (Scotland), Env. Archaeol. 14, 1-14.

532

Balasse, M. and Tresset, A. 2009. A key to the adaptation of Neolithic husbandry in the Orkneys: contribution of seaweed to the sheep diet at the Holm of Papa Westray, revealed through stable isotope analysis ( $\delta^{13}$ C and  $\delta^{18}$ O) of teeth, in: A. Ritchie (Ed.), On the Fringe of Neolithic Europe, Society of Antiquaries of Scotland, Edinburgh, pp. 74-82.

- 537
- 539 Balasse, M., Tresset, A., Ambrose, S.H., 2006. Stable isotope evidence ( $\delta^{13}$ C,  $\delta^{18}$ O) for 540 winter feeding on seaweed by Neolithic sheep of Scotland, J. Zool. 270, 170-176.
- 541
- 542 Balasse, M., Tresset, A., Dobney, K., Ambrose, S.H., 2005. The use of isotope ratios to 543 test for seaweed eating in sheep, J. Zool. 266, 283-291.
- 544
- 545 Barber, J., 1997. The Excavation of a Stalled Cairn at the Point of Cott, Westray,
- 546 Orkney, Scottish Trust for Archaeological Research, Edinburgh.
- 547
- 548 Barrett, J.H., Richards, M.P., 2004. Identity, gender, religion and economy: New isotope
- and radiocarbon evidence for marine resource intensification in early historic Orkney,
- 550 Scotland, Euro. J. Archaeol. 7, 249-271.

551 552 Bocherens, H., Drucker, D., 2003. Trophic level isotopic enrichments for carbon and 553 nitrogen in collagen: case studies from recent and ancient terrestrial ecosystems, Int. J. 554 Osteoarchaeol. 13, 46-53. 555 556 Boutton, T.W., 1991. Stable carbon isotope ratios of natural materials: II. Atmospheric, 557 terrestrial, marine and freshwater environments, in: Coleman, D.C., Fry, B. (Eds.), 558 Carbon Isotope Techniques, Academic Press, San Diego, pp. 173-185. 559 560 Britton, K., Müldner, G., Bell, M., 2008. Stable isotope evidence for salt-marsh grazing in 561 the Bronze Age Severn Estuary, UK: implications for palaeodietary analysis at coastal 562 sites, J. Archaeol. Sci. 35, 2111-2118. 563 Bronk Ramsey, C., OxCal 4.2, https://c14.arch.ox.ac.uk/, 2013. 564 Bronk Ramsey, C., Higham, T.F.G., Owen, D.C., Pike, A.W.G., Hedges, R.E.M., 2002. 565 566 Radiocarbon dates from the Oxford AMS system: Archaeometry datelist 31, 567 Archaeometry 44, 1-150. 568 569 Caumette, G., Ouypornkochagorn, S., Scrimgeour, C.M., Raab, A., Feldmann, J., 2007. 570 Monitoring the arsenic and lodine exposure of seaweed-eating North Ronaldsay sheep 571 from the gestational and suckling periods to adulthood by using horns as a dietary 572 archive, Env. Sci. Technol. 41, 2673-2679. 573 574 Caut, S., Angulo, E., Courchamp, F., 2009. Variation in discrimination factors (A15N and 575  $\Delta$ 13C): the effect of diet isotopic values and applications for diet reconstruction, J. Appl. 576 Ecol. 46, 443-453. 577 578 Chapman, V.J., Chapman, D.J., 1980. Seaweeds and their Uses, 3rd ed., Chapman 579 and Hall, London. 580 581 Clutton-Brock, J., 1979. Report on the mammalian remains other than rodents from 582 Quanterness, in: Renfrew, C. (Ed.), Investigations in Orkney, Thames and Hudson, 583 London, pp. 112-134. 584 585 Crozier, R., A taphonomic approach to the re-analysis of the human remains from the Neolithic chamber tomb of Quanterness, Orkney, Unpublished PhD thesis, Queen's 586 587 University Belfast, 2012. 588 589 DeNiro, M.J., 1985. Post-mortem preservation and alteration of *in vivo* bone collagen 590 isotope ratios in relation to palaeodietary reconstruction, Nature 317, 806-809. 591 592 Feldmann, J., John, K., Pengsprecha, P., 2000. Arsenic metabolism in seaweed-eating 593 sheep from Northern Scotland, Fresenius J. Anal. Chem. 368, 116–121. 594 595 Fenton, A., 1978. The Northern Isles: Orkney and Shetland, John Donald, Edinburgh. 596 597 Hallsson, S.V., 1964. The uses of seaweed in Iceland, in: De Virville, D., Feldman, J. 598 (Eds.), Proceedings of the Fourth International Seaweed Symposium, Pergamon Press,

- 599 Oxford, pp. 398–405.
- Hansen, H.R., Hector, B.L., Feldmann, J., 2003. A qualitative and quantitative study of
  the seaweed diet of North Ronaldsay sheep, Anim. Feed Sci. Technol. 105, 21-28.
- Heaton, T.H.E., 1987. The <sup>15</sup>N/<sup>14</sup>N ratios of plants in South Africa and Namibia:
  relationship to climate and coastal/saline environments, Oecol. 74, 236-246.
- 606
- Hedges, R.E.M., Reynard, L.M., 2007. Nitrogen isotopes and the trophic level ofhumans in archaeology, J. Archaeol. Sci. 34, 1240-1251.
- 609
  610 Indergaard, M., Minsaas, J., 1991. Animal and human nutrition, in: Guiry, M.D.,
  611 Blunden, G. (Eds.), Seaweed Resources in Europe: Uses and Potential, Wiley,
  612 Chichester, pp. 21–64.
- 613
- Jenkins, S.G., Partridge, S.T., Stephenson, T.R., Farley, S.D., Robbins, C.T., 2001.
  Nitrogen and carbon isotope fractionation between mothers, neonates, and nursing
  offspring, Oecol. 129, 336-341.
- 617
- Jones, J.R., Mulville, J., 2016. Isotopic and zooarchaeological approaches towards
  understanding aquatic resource use in human economies and animal management in
  the prehistoric Scottish North Atlantic Islands, J. Archaeol. Sci. Rep. 6, 665–677.
- Jones, J.R., Mulville, J., McGill, R.A.R., Evershed, R.P., 2012. Palaeoenvironmental modelling of  $\delta$ 13C and  $\delta$ 15N values in the North Atlantic Islands: understanding past marine resource use, Rapid Commun. Mass Spectrom. 26, 2399-2406.
- Kelly, F., 1997. Early Irish Farming, Dublin Institute for Advance Studies, Dublin.
- Lee-Thorp, J., Sealy, J., van der Merwe, N.J., 1989. Stable carbon isotope ratio
  differences between bone collagen and bone apatite, and their relationship to diet, J.
  Archaeol. Sci. 16, 585-599.
- 631632 Lee-Thorp, J.A., 2008. On isotopes and old bones, Archaeometry 50, 925-950.
- 633
  634 Longin, R., 1971. New method of collagen extraction for radiocarbon dating, Nature 230,
  635 241-242.
- 636
- Mainland, I., Towers, J., Ewens, V., Davis, G., Batey, C., Card, N., Downes, J., 2016.
  Toiling with teeth: An integrated dental analysis of sheep and cattle dentition in Iron Age
- 639 and Viking–Late Norse Orkney, J. Archaeol. Sci. Rep. 6, 837-855.
- 640

- Mainland, I.L., 2000. A dental microwear study of seaweed-eating and grazing sheepfrom Orkney, Int. J. Osteoarchaeol. 10, 93-107.
- Makkar, H.P.S., Tran, G., Valérie Heuzé, Giger-Reverdin, S., Lessire, M., Lebas, F.,
- Ankers, P., 2016. Seaweeds for livestock diets: A review, Anim. Feed Sci. Technol. 212, 1-7.

- 647
- 648 Martin, M., 1703. A Description of the Western Islands of Scotland Circa 1695, Andrew 649 Bell, London.
- McCormick, F., Buckland, P.C., 2003. The vertebrate fauna, in: Edwards, K.J., Ralston,
  I.B.M. (Eds.), Scotland After the Ice Age: Environment and Archaeology, 8000 BC AD
  1000, Edinburgh University Press, Edinburgh, pp. 83-103.
- 654
- McDonald, I., Wenham, G., Robinson, J.J., 1977. Studies on reproduction in prolific
  ewes. 3. The development in size and shape of the foetal skeleton, J. Agr. Sci. 89, 373391.
- Milhaud, G., Nezit, J., 1991. Molar development in sheep: morphology, radiography,
  microhardness, Rec. Méd. Vét. 167, 121-127.
- 661

- Montgomery, J., Beaumont, J., Jay, M., Keefe, K., Gledhill, A.R., Cook, G.T., Dockrill,
- 663 S.J., Melton, N.D., 2013. Strategic and sporadic marine consumption at the onset of the 664 Neolithic: increasing temporal resolution in the isotope evidence, Antiq. 87, 1060-1072.
- Moran, N.C., O'Connor, T.P., 1994. Age attribution in domestic sheep by skeletal and
  dental maturation: a pilot study of available sources, Int. J. Osteoarchaeol. 4, 267-285.
- Popkin, P.R.W., Baker, P., Worley, F., Payne, S., Hammon, A., 2012. The Sheep
  Project (1): determining skeletal growth, timing of epiphyseal fusionand morphometric
  variation in unimproved Shetland sheep of known age, sex, castration status and
  nutrition, J. Archaeol. Sci. 39, 1775-1792.
- 673

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C.,
Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P.,
Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen,
K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A.,
Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13
and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP,
Radiocarbon 55, 1869–1887.

- 681
- Renfrew, C., 1979. The chambered cairn at Quanterness: the excavation, in: Renfrew,
  C. (Ed.), Investigations in Orkney, Thames and Hudson, London, pp. 44-72.
- Richards, M.P., Hedges, R.E.M., 1999. Stable isotope evidence for similarities in the
  types of marine foods used by Late Mesolithic humans on the Atlantic coast of Europe,
  J. Archaeol. Sci. 26, 717-722.
- 688
- Richards, M.P., Fuller, B.T. and Molleson, T.I. 2006. Stable isotope palaeodietary study
  of humans and fauna from the multi-period (Iron Age, Viking and Late Medieval) site of
  Newark Bay, Orkney, J. Archaeol. Sci. 33, 122-131.
- 692
- Ritchie, A. (Ed.), 2009. On the Fringe of Neolithic Europe: Excavation of a ChamberedCairn on the Holm of Papa Westray, Orkney, Society of Antiquaries of Scotland,

- 695 Edinburgh.
- 696

Schoeninger, M.J., DeNiro, M.J., 1984. Nitrogen and carbon isotopic composition of
bone collagen from marine and terrestrial animals, Geochim. Cosmochim. Acta 48, 625639.

700

Schulting, R.J., 2013. On the northwestern fringes: Earlier Neolithic subsistence in
Britain and Ireland as seen through faunal remains and stable isotopes, in: Colledge, S.,
Conolly, J., Dobney, K., Manning, K., Shennan, S. (Eds.), The Origins and Spread of
Stock-Keeping in the Near East and Europe, Left Coast Press, Walnut Creek, California,
pp. 313-338.

706

Schulting, R.J., Richards, M.P., 2009. Radiocarbon dates and stable isotope values on
human remains, in: Ritchie, A. (Ed.), On the Fringe of Neolithic Europe, Society of
Antiquaries of Scotland, Edinburgh, pp. 67-74.

710

Schulting, R.J., Sheridan, A., Crozier, R., Murphy, E., 2010. Revisiting Quanterness:

new AMS dates and stable isotope data from an Orcadian chamber tomb, Proc. Soc.Antiq. Scotland 140, 1-50.

714

Schulting, R.J., Tresset, A., Dupont, C., 2004. From harvesting the sea to stock rearing
along the Atlantic façade of north-west Europe, Env. Archaeol. 9, 143-154.

- Sharp, Z., 2007. Principles of Stable Isotope Geochemistry, Pearson Prentice Hall,
  Upper Saddle River, NJ.
- 720
  721 Stuiver, M., Polach, H.A., 1977. Reporting of <sup>14</sup>C data, Radiocarbon 19, 355-363.
  722

Towers, J., Mainland, I., Montgomery, J., Bond, J., 2016 (early view). Calving

- seasonality at Pool, Orkney during the first millennium AD: an investigation using intra tooth isotope ratio analysis of cattle molar enamel, Env. Archaeol. doi:
- 726 10.1080/14614103.2015.1116214
- van Klinken, G.J., 1999. Bone collagen quality indicators for palaeodietary and
  radiocarbon measurements, J. Archaeol. Sci. 26, 687-695.
- 730

Wood, J.W., Milner, G.R., Harpending, H.C., Weiss, K.M., 1992. The osteological
paradox: Problems of inferring prehistoric health from skeletal samples, Curr. Anthropol.
33, 343-370.

- 734
- Zeder, M.A., Lapham, H.A., 2010. Assessing the reliability of criteria used to identify
  postcranial bones in sheep, Ovis, and goats, Capra, J. Archaeol. Sci. 37, 2887-2905.
- 738

739 740	Figures and Tables
740 741 742	Figure 1. Map of Orkney showing locations mentioned in the text.
743 744	Figure 2. Plot of $\delta^{13}$ C and $\delta^{15}$ N results from Quanterness
745 746 747	Figure 3. OxCal 4.2 (Bronk Ramsey 2013) plot of calibrated faunal dates from Quanterness (excluding UBA-18427, 908 $\pm$ 25 BP).
748 749 750 751 752	Figure 4. Plot of bone collagen $\delta^{13}$ C and $\delta^{15}$ N measurements on sheep/goat from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting and Richards 2009). The three squares identify low values thought to be medieval intrusions, and are not included in the regression.
753 754 755 756	Figure 5. Plot of bone collagen $\delta^{13}$ C and $\delta^{15}$ N measurements on humans and fauna from Neolithic and Bronze Age Orkney (data: this paper; Jones and Mulville 2016; Schulting <i>et al.</i> 2010; Schulting and Richards 2009).
757 758 759 760 761	Figure 6. Plot of sequential enamel $\delta^{13}$ C and $\delta^{18}$ O measurements on sheep third molars from a) Holm of Papa Westray North, and b) Knap of Howar (Balasse and Tresset 2009).
761 762 763	Table 1. Quanterness fauna sample details and results of $\delta^{13}C$ and $\delta^{15}N$ analysis.
764 765	Table 2. Summary statistics for Quanterness fauna $\delta^{13}C$ and $\delta^{15}N$ results.
766 767	Table 3. Results of <sup>14</sup> C dating. Mixed marine-terrestrial curves are used for the three juvenile sheep with significantly enriched <sup>13</sup> C (Reimer <i>et al.</i> 2013).













Figure 6a



Figure 6b