

*Diet and herding strategies in a changing environment: stable isotope analysis of Bronze Age and Late Antique skeletal remains from Ya'amūn, Jordan*

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Accepted Version

Sandias, M. and Müldner, G. (2015) Diet and herding strategies in a changing environment: stable isotope analysis of Bronze Age and Late Antique skeletal remains from Ya'amūn, Jordan. *Journal of Archaeological Science*, 63. pp. 24-32. ISSN 0305-4403 doi: <https://doi.org/10.1016/j.jas.2015.07.009> Available at <http://centaur.reading.ac.uk/42502/>

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Published version at: <http://www.sciencedirect.com/science/article/pii/S030544031500237X>

To link to this article DOI: <http://dx.doi.org/10.1016/j.jas.2015.07.009>

Publisher: Elsevier

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1 **Diet and herding strategies in a changing environment: stable isotope**  
2 **analysis of Bronze Age and Late Antique skeletal remains from**  
3 **Ya‘amūn, Jordan**

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8

9 **Abstract**

10 Carbon and nitrogen stable isotope ratios of 45 human and 23 faunal bone collagen samples were  
11 measured to study human diet and the management of domestic herbivores in past Jordan,  
12 contrasting skeletal remains from the Middle and Late Bronze Age and the Late Roman and  
13 Byzantine periods from the site of Ya‘amūn near Irbid. The isotope data demonstrate that the  
14 management of the sheep and goats changed over time, with the earlier animals consuming more  
15 plants from semi-arid habitats, possibly because of transhumant herding strategies. The isotope  
16 data for fish presented here are the first from archaeological contexts from the Southern Levant.  
17 Although fish of diverse provenance was available at the site, human diet was predominately based  
18 on terrestrial resources and there was little dietary variability within each time-period. Isotopic  
19 variation between humans from different time-periods can mostly be explained by ‘baseline shifts’  
20 in the available food sources; however, it is suggested that legumes may have played a more  
21 significant role in Middle and Late Bronze Age diet than later on.

22 **Keywords:** carbon and nitrogen isotopes; bone collagen; Bronze Age; Roman period; Byzantine  
23 period; fish;

## 24 **Highlights**

25  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values were employed to reconstruct herd management and human diet in past Jordan

26 Bronze Age ovicaprids consumed more plants from semi-arid habitats than Late Roman/Byzantine  
27 animals

28 The data suggest drier conditions or transhumant herd management in the Bronze Age

29 Differences in the human data can mostly be explained by environmental changes.

30

## 31 **1. Introduction**

32 The archaeology of the Near East is one of the areas where carbon and nitrogen isotope analysis has  
33 made a considerable impact in recent years, contributing, for example, to our understanding of early  
34 husbandry practices (Makarewicz and Tuross, 2012; Pearson *et al.*, 2007;), the heterogeneous  
35 origins of people and animals (Hartman *et al.*, 2013, Thompson *et al.* 2008), the contribution to  
36 human diet of specific food resources (Lösch, *et al.*, 2006, Richards *et al.*, 2003, Thompson *et al.*,  
37 2005) and the development of social complexity (Makarewicz, 2013, Pearson *et al.*, 2013). One of  
38 the key strengths of the method is where it permits diachronic comparisons of isotope data from  
39 individual sites, enabling the tracing of continuity or change of subsistence strategies and  
40 environmental contexts through time. Using this approach, carbon stable isotope analysis of dental  
41 enamel of Bronze Age and Byzantine burials from the sites of Ya‘amūn, Sa‘ad and Yasideh in  
42 North Jordan suggested remarkable homogeneity in diet across time and sites (Al-Shorman, 2003,  
43 2004). A complementary study of carbon and nitrogen stable isotope ratios in dentinal collagen of  
44 human teeth recovered from Ya‘amūn, Sa‘ad and Yasideh also indicated continuity (King, 2001).  
45 Because of the samples chosen, both studies explored diet only over the relatively short period of

46 tooth formation in childhood and early adolescence and the lack of site- and period-specific faunal  
47 baseline data did not allow monitoring for differences in environmental settings in this ecologically  
48 diverse region. Building on this previous research, the present study adds new evidence from carbon  
49 and nitrogen stable isotope analysis of bone collagen of human and faunal remains from Ya‘amūn,  
50 in an attempt to reconstruct animal and human long-term adult diet at the site during two profoundly  
51 different time periods. We aim to explore how Bronze Age and Late Antiquity consumption profiles  
52 reflect changes in landscape exploitation and economic strategies, which are of great significance  
53 for understanding the way of life in northern Jordan in the past.

## 54 **2. The site of Ya‘amūn**

55 Jordan’s territory is characterised by high variability in vegetation, physiography, hydrology, and  
56 climate. Four of the five vegetation regions identified in the Middle East, the Mediterranean region,  
57 the Irano-Turanian steppe, the Saharo-Arabian region and the Sudanian region are present in Jordan  
58 (Zohary, 1973; Palmer 2013, Figure 1a). Ya‘amūn is located in the northern part of the Western  
59 Highlands at about eight hundred metres above sea level, 23 km southeast of Irbid. Here, current  
60 mean annual precipitation is ~400mm (Cordova, 2007). However, within few tens of kilometres of  
61 Ya‘amūn the amount of rainfall decreases drastically to less than 200 mm, with the dry Jordan  
62 River Valley to the west and the steppe and desert landscapes to the east (Figure 1b). The region  
63 around Ya‘amūn therefore presents as a mosaic of ecosystems, where oak forests, Mediterranean  
64 low vegetation and steppe habitats are in relative close proximity (Al-Eisawi, 1985).

65 Occupation at Ya‘amūn spanned from the Early Bronze Age, beginning at c. 3600 cal BCE to the  
66 Ayyubid-Mamluk period, thirteenth to sixteenth century CE (dates as in Adams, 2008). Since the  
67 first season of excavation, several tombs of variable type, chamber and shaft tombs as well as  
68 natural caves used for burial have been identified and excavated (Renfro and Cooper, 2000, Rose,  
69 2002, Rose *et al.*, 2007, Rose *et al.*, 2003). As most of these have been robbed in modern times

70 and/or reused during the Islamic and later periods a detailed description of burial rites is not  
71 available (Rose, 2005). Excavations of the tombs and of the Bronze Age settlement have produced  
72 Mycenaean and Cypriot ceramic sherds, Egyptian scarabs and a Mittanian cylinder seal, which  
73 demonstrate trade and contact with different areas of the Mediterranean (Rose, 2001). During Late  
74 Antiquity (approx. 4<sup>th</sup>– 7<sup>th</sup> century CE (Watson, 2008)), Ya‘amūn was a thriving agricultural  
75 settlement which contributed to the evidently booming economy in the Late Roman and particularly  
76 the Byzantine period (Cameron, 1993, Freeman, 2008, Kennedy, 2007, Parker 1999, Rosen, 2007).  
77 The prosperity of Ya‘amūn is shown by various olive and wine presses and by numerous carved  
78 water cisterns (El-Najjar and Rose, 2003, Rose *et al.*, 2007). Furthermore, the mosaics of the  
79 Ya‘amūn Byzantine church are of equally high quality as those in contemporaneous churches of the  
80 nearby Decapolis cities (El-Najjar *et al.*, 2001, Rose *et al.*, 2007).

### 81 **3. Diet and environmental reconstruction by carbon and nitrogen stable isotope** 82 **analysis of bone collagen**

83 The ratios of the stable isotopes of carbon ( $^{13}\text{C}/^{12}\text{C}$ ) and nitrogen ( $^{15}\text{N}/^{14}\text{N}$ ) are amongst the most  
84 frequently measured in ancient skeletal remains for diet and environmental reconstruction. These  
85 ratios are conventionally referred to relative to a standard as  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values, respectively.  
86 Due to isotope partitioning, isotopes of the same element are unequally distributed in different types  
87 of soils, and in different water bodies, plants and animals (Ehleringer and Rundel, 1989, Hoefs,  
88 2009). As a result, organisms from different ecosystems can have distinct isotopic signatures and,  
89 similarly, their isotopic composition may vary according to their trophic level (Kelly, 2000).  
90 Feeding experiments have shown that the stable isotope ratios measured in human and animal bone  
91 collagen reflect the isotopic composition of plant and animal foods, and especially of the dietary  
92 protein (Ambrose and Norr, 1993, Tieszen and Fagre, 1993, Froehle *et al.*, 2010), consumed over  
93 several years of life (Hedges *et al.*, 2007).

94    Photosynthesis is the main source of carbon isotopic variation in terrestrial ecosystems. According  
95    to their photosynthetic pathway, terrestrial plants fall into two main groups, C<sub>3</sub> and C<sub>4</sub> plants. C<sub>3</sub>  
96    plants are characteristic of the temperate environments and include most plants used for human  
97    consumption such as wheat, barley, most fruits, legumes and nuts. In contrast, C<sub>4</sub> plants are adapted  
98    to high light intensity, high temperatures and frequent water shortages. They include many tropical  
99    grasses and the cultural crops millet, sorghum, maize and sugar cane (van der Merwe, 1989).  
100    During photosynthesis, C<sub>3</sub> plants tend to incorporate less <sup>13</sup>C by discriminating more than C<sub>4</sub> plants  
101    against <sup>13</sup>CO<sub>2</sub>. The tissues of C<sub>3</sub> plants therefore have lower δ<sup>13</sup>C values than C<sub>4</sub> plants. Mean δ<sup>13</sup>C  
102    values are -26 ‰ and -12.5 ‰ for C<sub>3</sub> and C<sub>4</sub> plants, respectively (Smith and Epstein, 1971). These  
103    differences in the isotope values of the plants are reflected in the isotopic signature of the  
104    consumers, although absolute values are slightly changed by different metabolic pathways (DeNiro  
105    and Epstein, 1978 and studies summarised in Ambrose and Norr 1993). The carbon isotope  
106    composition of bone collagen therefore provides an indication of the relative contributions of C<sub>3</sub>  
107    and C<sub>4</sub> plants to the diet of herbivores and, in turn, may give indication of their abundance in the  
108    environment. For the humans, who in most cases eat an omnivorous diet, δ<sup>13</sup>C values can reflect  
109    either direct consumption of plants or the isotopic composition of meat and dairy products derived  
110    from C<sub>3</sub>- or C<sub>4</sub>-fed animals (Ambrose, 1993). δ<sup>13</sup>C values are also used to identify consumption of  
111    marine resources as marine foods have substantially higher δ<sup>13</sup>C than terrestrial C<sub>3</sub> foods (Richards  
112    and Hedges, 1999, Schoeninger and DeNiro, 1984). However, within the environmental context of  
113    Jordan, it is the variable reliance on C<sub>3</sub> and C<sub>4</sub> plants that is likely to explain most carbon isotope  
114    variation in animals and humans.

115    Bone collagen δ<sup>15</sup>N values are mainly used as an indicator of the trophic position of an organism in  
116    the foodweb, an attribute which is based on the enrichment of consumer tissues in <sup>15</sup>N with each  
117    step up the food chain (DeNiro and Epstein, 1981, Minagawa Wada, 1984, Schoeninger and  
118    DeNiro, 1984), breastfeeding mammals being at the top of this sequence (Fuller *et al.*, 2006).

119 Although trophic level enrichments are consistently observed in modern foodwebs, estimating the  
120 relative contributions of plant and animal protein in omnivorous diets is complicated by a number  
121 of factors, not the least uncertainty about the exact mechanisms behind the trophic level effect and  
122 how the diet-tissue spacing is affected by various nutritional and metabolic factors (Vanderklift and  
123 Ponsard, 2003, Caut *et al.*, 2009). While a full trophic offset in collagen stable isotope studies is  
124 commonly estimated as between 3 and 5‰ (Bocherens and Drucker, 2003), higher values in  
125 humans have also been suggested (Hedges and Reynard, 2007, O'Connell *et al.*, 2012). It is  
126 generally acknowledged that, because most plants are relatively low in protein, their contribution to  
127 the diet will be underrepresented in the collagen stable isotope signal; however, another issue that  
128 has been raised more recently is the fact that the isotopic composition of plant foods usually needs  
129 to be estimated from the bone collagen values of domestic herbivores which may not always give a  
130 truthful reflection of the plants used for human consumption (Fraser *et al.*, 2013). Despite these  
131 issues, studies have shown that the use of  $\delta^{15}\text{N}$  as a broad indicator of the level of animal protein  
132 consumption in humans is overall sound, even though they cannot distinguish between different  
133 foods of animal origin such as between meat and dairy products (O'Connell and Hedges, 1999,  
134 Petzke *et al.*, 2005).

135 Although bone stable isotope data are primarily a reflection of diet, isotope analysis of faunal,  
136 specifically herbivore remains has also been used to indirectly reconstruct environmental  
137 conditions, the underlying principle being that herbivore data provide an averaged isotope value for  
138 the local vegetation, the isotopic composition of which will vary according to a number of  
139 environmental and climatic factors (Hedges *et al.*, 2004, van Klinken *et al.*, 1994). Most obviously,  
140 herbivore  $\delta^{13}\text{C}$  values may give information about the proportion of  $\text{C}_3$  *versus* aridity-adapted  $\text{C}_4$   
141 plants in an area – although the feeding preferences of individual species must also be taken into  
142 account (Ambrose and DeNiro, 1986, Hartman *et al.*, 2013). Variations in temperature or rainfall  
143 patterns, among others, also affect the isotopic composition of  $\text{C}_3$  plants and may therefore be



144 traceable in herbivore tissues (Hartman and Danin, 2010, van Klinken *et al.*, 1994). For nitrogen  
145 isotope ratios, a marked inverse correlation has been demonstrated between bone collagen  $\delta^{15}\text{N}$   
146 values and rainfall, so that herbivores living in arid environments show elevated  $\delta^{15}\text{N}$  values  
147 (Ambrose and DeNiro, 1986, Heaton *et al.*, 1986). While physiological mechanisms have been  
148 proposed in explanation (Ambrose, 1991, Sealy *et al.*, 1987), it is now thought most likely that the  
149 ‘rainfall effect’ is due to the  $^{15}\text{N}$ -enrichment of plants, through the effects of denitrification and  
150 ammonia volatilization in the soil (Hartman, 2011, Heaton, 1987, Murphy and Bowman, 2006,  
151 Schwarcz *et al.*, 1999). A linkage has also been found between high  $\delta^{15}\text{N}$  values in cultivated plants  
152 and use of manure on fields (Bogaard *et al.*, 2007, Fraser *et al.*, 2011) and should be kept in mind  
153 when comparing the  $\delta^{15}\text{N}$  values of humans and their domestic animals.

154

#### 155 **4. Materials and Methods**

156 The excavation of the Ya‘amūn tombs led to the identification of Middle Bronze Age, Late Bronze  
157 Age, Late Roman and Byzantine burials, with dating achieved through a systematic study of pottery  
158 fragments and grave goods, and of the architectural features (Al-Shorman, 2004, Barnes, 2003,  
159 Burke and Rose, 2001, El-Najjar and Rose, 2003, El-Najjar *et al.*, 2001, Rose *et al.*, 2007). From  
160 the skeletal remains made accessible at the Department of Archaeology and Anthropology of the  
161 University of Yarmouk (Irbid, Jordan), it was possible to sample 45 individuals. Of these, 22 date to  
162 the Middle-Late Bronze Age, while 23 date to the Late Roman-Byzantine period. A further 23  
163 samples were obtained from the remains of adult domestic ungulates and fishbone recovered from  
164 well-dated contexts. The entire assemblage was highly fragmented. In the case of the human  
165 remains, this prevented the assessment of age and sex. For the faunal remains, it was usually  
166 problematic to distinguish between sheep (*Ovis aries*) and goats (*Capra hircus*) on morphological  
167 grounds. These are therefore collectively referred to as domestic ovicaprids or as sheep/goats (for

168 more information on sampling processing and analysis see Supplementary Information). Isotopic  
169 differences between the two species on account of their feeding ecology are not expected in the  
170 environmental context of the southern Levant (see Hartman et al., 2013: S1).

## 171 **5. Results**

172 The  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  isotope data and quality indicators of the faunal and human bone samples from  
173 Ya‘amūn are reported in Tables S1 and S2 (see Supplementary Materials), respectively. Fifty (18  
174 faunal and 32 humans samples) out of 68 bone specimens yielded good quality collagen (Ambrose  
175 1990; DeNiro 1985). Descriptive statistics for each of the sample groups are presented in Table 1.  
176 The highest variability was found amongst the Bronze Age (MBA and LBA combined) animals,  
177 while the Late Antique (LR-Byz) sheep/goats presented the lowest. The  $\delta$ -values of the domestic  
178 herbivores, illustrate a clear difference in the diet of Bronze Age and Late Antique sheep/goats with  
179 apparently decreased  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  in the later periods (Figure 2). Although the difference is  
180 statistically significant for  $\delta^{15}\text{N}$  only (Independent Samples Mann-Whitney test with exact  
181 probabilities to account for small sample sizes:  $U=11.5$ ,  $p=0.537$  for  $\delta^{13}\text{C}$ ;  $U=1.0$ ,  $p=0.009$  for  
182  $\delta^{15}\text{N}$ ), the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of the MBA/LBA sheep-goats are clearly correlated ( $r^2=0.75$ ).  
183 While the later ovicaprids had a more monotonous diet, the two LR/Byz *Bos* specimens plot  
184 relatively far apart, with a 3.2‰ difference in  $\delta^{13}\text{C}$  and a 4.3‰ difference in  $\delta^{15}\text{N}$  values. In Figure  
185 3, the human values are compared to the terrestrial fauna. No statistically significant differences  
186 were found between human isotope values from MBA and LBA (Independent samples Mann-  
187 Whitney test,  $U=22.5$ ,  $p=0.536$  for  $\delta^{13}\text{C}$  and  $U=18.0$ ,  $p=1.0$  for  $\delta^{15}\text{N}$ ), and Late Roman and  
188 Byzantine Ya‘amūn ( $U=8.5$ ,  $p=0.667$  for  $\delta^{13}\text{C}$  and  $U=4.5$ ,  $p=1.83$  for  $\delta^{15}\text{N}$ ). Consequently these  
189 were pooled into one Bronze Age and one Late Antique group. The differences between the Bronze  
190 Age and Late Antique humans are statistically significant for both carbon and nitrogen

191 (Independent-sample Mann-Whitney test,  $U=49.0$ ,  $p=0.002$  for  $\delta^{13}\text{C}$  and  $U=55.5$ ,  $p=0.005$  for  
192  $\delta^{15}\text{N}$ ).

193

## 194 **6. Discussion**

### 195 *6.1 The fauna from Ya'amūn*

196 Overall, the range of  $\delta^{13}\text{C}$  values of the domestic ungulates from Ya'amūn indicates that they were  
197 grazing in an environment where  $\text{C}_3$  vegetation dominates over  $\text{C}_4$  vegetation. These results are in  
198 agreement with the data presented previously by Al-Shorman (2004, 2003) and King (2001) on the  
199 human diet and are also consistent with the vegetation composition around the site in modern times  
200 (Al-Eisawi 1996, Shomer-Ilan *et al.*, 1981, Vogel *et al.*, 1986, Winter, 1981). Nevertheless, the  
201 most positive  $\delta^{13}\text{C}$  (-16.6‰ for sheep/goat and -15.6‰ for cattle, Table 1) indicate the inclusion of  
202 varying and sometimes substantial amounts of  $\text{C}_4$  plants in the animals' diet. These higher  $\delta^{13}\text{C}$   
203 values are correlated with raised  $\delta^{15}\text{N}$  values which are also consistent with grazing in arid regions  
204 (Hartman and Danin, 2010, Heaton, 1987, see section 3 above).

205 The differences observed in the sheep/goat data from the Bronze Age and Late Antiquity (Figure 2)  
206 are consistent with suggestions that climate in the MBA and LBA in the Southern Levant was dry  
207 and similar to present conditions, while sedimentological and palynological evidence as well as  
208 speleothem oxygen isotope analyses unequivocally indicate wetter conditions in the Roman and  
209 Byzantine periods (Bookman *et al.*, 2004; Enzel *et al.*, 2003; Neumann *et al.*, 2007; Orland *et al.*,  
210 2009; Finné *et al.*, 2011; Rambeau and Black 2011). Nevertheless, if climatic conditions in the  
211 MBA/LBA were indeed similar to the present day and even more so if, as has also been suggested,  
212 they were slightly wetter (see Rambeau and Black 2011: 99), it is unlikely that the MBA/LBA  
213 sheep/goats with elevated carbon and/or nitrogen isotope values (at least half of what is, admittedly,  
214 a small sample) could have acquired these by freely foraging in the immediate hinterland of the site.

215 Ya'amūn itself is situated in the xeric Mediterranean phytogeographic zone which receives modest  
216 rainfall (currently ~400mm/year) and therefore has little C<sub>4</sub> vegetation, which only becomes notable  
217 in areas with less than ~350mm annual precipitation . The observed δ-values are therefore  
218 consistent with animals grazing in much drier environments and these indeed provide the best  
219 parallels among published data. According to the large reference data-set compiled by Hartman *et*  
220 *al.* (2013), the MBA/LBA sheep/goats from Ya'amūn are most consistent with ovicaprids feeding  
221 in the desert zone, although similar isotope values have also been produced for goats from a semi-  
222 arid steppe environment (Makarewicz and Tuross, 2012). In any case, the Bronze Age herbivore  
223 data from Ya'amūn suggest that sheep/goat were herded away from the site for at least part of the  
224 year. The isotope values for the sheep/goat from Ya'amūn are almost identical to another small  
225 data-set of MBA sheep from Tell Al-Husn, only a few kilometres to the north (Al-Bashaireh and  
226 Al-Muheisen, 2011). Here, elevated isotope values were only observed in three very young  
227 individuals and the <sup>15</sup>N-enrichment was consequently attributed to a 'suckling effect'; however, the  
228 consumption of mother ewes' milk cannot easily explain the relatively large difference in δ<sup>13</sup>C  
229 between the young and adult sheep (Balasse *et al.*, 1999), which approaches 2‰. Instead, the bones  
230 of the suckling sheep may record a seasonal shift in the diet of the mothers, during the gestation  
231 period and early life of their lambs, to include <sup>13</sup>C-enriched graze. Transhumance is standard  
232 practice amongst the traditional pastoralists in the southern Levant who, usually, spend the months  
233 between November and April leading herds to the green pastures that develop in arid and semi-arid  
234 areas during the rainfall season. This system has the added advantage of keeping the animals away  
235 from agricultural fields during the crop growing season (Levy, 1983, Safrai, 2004, 93). Texts dated  
236 to the Middle and Late Bronze periods of Syria-Palestine and Anatolia describe various strategies  
237 for managing domestic herbivores (Liverani, 1988, 374, 437), and how, for instance, the sheep  
238 owned by the elites spent most of the year away from the city to return only for the shearing season  
239 (Snell, 1997, 72, 126). Another scenario is that animals raised at sites in the more arid zones were

240 brought to Ya‘amūn, which fits with artefactual evidence that the site was part of a network of  
241 commercial exchanges connecting north Jordan with the wider eastern Mediterranean (Bourke *et*  
242 *al.*, 2006, Strange, 2008), and would also explain why only part of the MBA/LBA sheep/goat  
243 sample exhibit the raised stable isotope values.

244 In contrast, the Late Roman/Byzantine animals were feeding almost entirely, if not exclusively, on  
245 C<sub>3</sub> plants and their δ<sup>15</sup>N values are significantly lower than in the earlier animals. Assuming, as  
246 Hartman *et al.* (2013: 4372) argue, that the wetter climatic conditions in Late Antiquity did not  
247 significantly shift the boundaries of environmental zones in the region, this suggests that the  
248 sheep/goats of this later period were more restricted in their mobility. They would have grazed on  
249 unused fields and between the orchards in the surroundings of Ya‘amūn where conditions were  
250 relatively moist because of wide-ranging irrigation. It is known that vine leaves and trimmings were  
251 sometimes used as animal fodder (Horden and Purcell, 2000, 214) and these must have been  
252 abundant at Ya‘amūn, where vine cultivation was extensive (see above).

253 There are too few cattle data to attempt reconstructing husbandry regimes, but it is nevertheless  
254 interesting to observe that the two Late Antique cattle have sharply diverging δ<sup>13</sup>C and δ<sup>15</sup>N values  
255 (Figure 2). While one plots close to the contemporaneous sheep/goats, the other has substantially  
256 higher δ<sup>13</sup>C and δ<sup>15</sup>N values, suggesting that it fed in a much drier environmental zone and/or an  
257 area where C<sub>4</sub> fodder crops had been adopted (Copley *et al.*, 2004). The animal therefore suggests  
258 that livestock was brought to Late Antique Ya‘amūn from the outside.

259 Ya‘amūn freshwater and marine fish isotope values (Table S1, Figure 4) are comparable with  
260 results from archaeological fish from Greece (Vika & Theodoropoulou 2012). The values for the  
261 marine species, in particular, add to a growing corpus of data that show fish from the Mediterranean  
262 to be <sup>13</sup>C-enriched and <sup>15</sup>N-depleted compared to animals from the North Atlantic. The observed  
263 differences in δ<sup>15</sup>N between the fish samples can be explained by differences in trophic level

264 (Froese and Pauly, 2014) and variation in the isotopic composition of aquatic primary producers  
265 (Ambrose 1993; France 1995; Fuller 2012b; Katzenberg & Weber 1999; Schoeninger & DeNiro  
266 1984). Particularly notable is the stark difference in  $\delta^{13}\text{C}$  between the two LR/Byz samples of the  
267 freshwater genus *Tilapia*, which exceeds 10‰ and indicates that these specimens lived in very  
268 different environments. The  $\delta^{13}\text{C}$  values for modern *Tilapia* from Lake Tiberias (Zohary *et al.*,  
269 1994), once corrected for the offset between muscle and bone collagen as well as lipid content, are  
270 very close to the relatively  $^{13}\text{C}$ -depleted value observed for YMNTfb100. An origin from the river  
271 Jordan or the Lake itself therefore appears plausible. The same may then be true for the specimen of  
272 *Clariidae* (catfish, YMNTfb102), as variation between the two could mostly be accounted for by  
273 differences in trophic level. *Tilapia* are also known to inhabit coastal rivers, including those of the  
274 southern Levant (Van Neer *et al.*, 2000) and a significant input from marine biomass could explain  
275 why specimen YMNTfb101 is substantially  $^{13}\text{C}$ -enriched over YMNTfb100. Nevertheless, Vika  
276 and Theodoropoulou (2012) have observed similar carbon isotope values for freshwater fish from  
277 Greece. *Tilapia* are bottom feeders and it is possible that their foodwebs are  $^{13}\text{C}$ -enriched by poor  
278 availability of  $\text{CO}_2$  in warm and stagnant waters (France, 1995, Hecky and Hesslein, 1995), perhaps  
279 combined with a hard water effect in a region where marine carbonate is the dominant geological  
280 substrate (Day, 1996). Further isotope studies on freshwater fish from the Levant will be necessary  
281 to test this hypothesis.

## 282 6.2 *The inhabitants of Ya'amūn*

283 The isotope values show that terrestrial  $\text{C}_3$ -derived resources dominated human diet at Ya'amūn.  
284 The isotopic differences between Bronze Age and Late Antique humans mirror those between the  
285 sheep/goats from both periods and suggest that much of what first appears as dietary variation can  
286 instead be explained by a baseline-shift in the isotopic composition of available food sources  
287 (Figure 3). Because of the impact of water availability on carbon isotope discrimination of  $\text{C}_3$  plants

288 during photosynthesis (Farquhar *et al.*, 1989), it is likely that the plant foods available at Ya‘amūn  
289 in the Bronze Age were also  $^{13}\text{C}$ -enriched over those cultivated under the wetter conditions of the  
290 Late Roman/Byzantine period. It should be noted that the same cannot necessarily be assumed for  
291 plant  $\delta^{15}\text{N}$  values as these are determined by numerous complex mechanisms (Evans, 2001,  
292 Högberg, 1997). Cultivated fields especially may be subject to additional measures such as the  
293 application of animal fertilizers (Fraser *et al.*, 2011). Despite significant differences in the isotopic  
294 composition of the bone collagen, human diet between the two time periods may therefore not have  
295 varied greatly in terms of the actual staple foods consumed and their relative proportions.

296 In this context, the relatively large difference in the average  $\delta^{15}\text{N}$  human-herbivore offset  
297 ( $\Delta^{15}\text{N}_{\text{human-herbivore}}$ ), which is 3.5‰ in the Late Antique but only 0.3‰ in the Bronze Age sample,  
298 requires some discussion. If herbivore  $\delta^{15}\text{N}$  were used to estimate the nitrogen isotope composition  
299 of plants consumed by humans and the spacing between humans and animals was therefore taken as  
300 an indicator for the relative contributions of plant and animal protein to the human diet (Hedges and  
301 Reynard, 2007), these data would suggest that Bronze Age diet was almost entirely based on plant  
302 foods, while humans in Late Antiquity habitually consumed large amounts of animal protein (~  
303 70% of the dietary protein according to Hedges and Reynard’s (2007) ‘standard model’, even if a  
304 generous trophic level offset of +5‰ is used). Either of these extreme scenarios seems unlikely in  
305 light of evidence for diet in these periods available from other sources (Grigson, 1998, 256; Safrai,  
306 2004, 96).

307 The human isotope data from MBA/LBA Ya‘amūn are almost identical to those obtained from  
308 EBA/MBA Tell Al-Husn (mean  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values  $\pm 1$  s.d.:  $-18.5 \pm 0.4\text{‰}$  and  $8.7 \pm 0.8$ ,  $n=10$ ), and  
309 suggest that the subsistence regime reflected was typical for the wider region (Al-Bashaireh and Al-  
310 Muheisen, 2011). It cannot be denied that staple foods derived from  $\text{C}_3$  cereals such as wheat and  
311 barley made up the bulk of the diet at this time (Zohary and Hopf, 2000; see Snell, 1997; for Jordan

312 see Bourke *et al.*, 2003; McNicoll *et al.*, 1992; Tubb 1988; Tubb *et al.*, 1997). Nevertheless, the  
313 faunal assemblage from BA Ya‘amūn itself as well as nearby sites such as Pella (Bourke *et al.*,  
314 1994, Bourke *et al.*, 1998) demonstrate that sheep and goat husbandry was well-established in the  
315 region during the Bronze Age. While the emphasis may have been on wool production processing  
316 of surplus dairy and the consumption of meat from animals that had outlived their usefulness would  
317 have been an integrated part of this economy (Grigson, 1998, 256). If it is therefore unlikely that the  
318 human diet was almost entirely plant-based, the relatively low  $\delta^{15}\text{N}$  values in the BA humans  
319 compared to the animal data need additional explanation. Pulses, especially lentils, were important  
320 protein-rich foods and a means of crop and diet diversification in the entire Mediterranean area  
321 since the beginning of agriculture (Grigson, 1998, Horden and Purcell, 2000, 203). Like other  
322 leguminous plants, they are able to fix nitrogen directly from the atmosphere and, as a result, are  
323 habitually  $^{15}\text{N}$ -depleted compared to other crops. Their regular inclusion in the diet would therefore  
324 have the effect of lowering the  $\delta^{15}\text{N}$  of human consumers, potentially masking the consumption of  
325 animal products (Fraser *et al.*, 2013).

326 If the human-herbivore  $\delta^{15}\text{N}$  offset therefore likely underrepresents the role of animal products in  
327 the Bronze Age diet at least to an extent, the opposite may be true for the Late Roman/Byzantine  
328 sample. It is well-established that cereals, in the form of wheat or barley bread, contributed the  
329 majority of the daily caloric intake in Roman-period Palestine, while the degree to which animal  
330 products were part of everyday diet varied according to wealth and, particularly for fish, to the  
331 distance from the place of production (Broshi, 1986, Dar, 1995, Garnsey, 1999:16, Safrai 2004,  
332 Wilkins and Hill, 2006). Ya‘amūn in Late Antiquity was the site of intensive agriculture, and  
333 manuring was widely practiced in Romano-Byzantine Palestine (Almagro, 2007). The herbivore  
334  $\delta^{15}\text{N}$  may therefore well underestimate the nitrogen isotope composition of the cultivated plants (see  
335 Fraser *et al.*, 2013). Written sources from the region also describe a system of crop rotation where  
336 wheat fields were periodically turned over to leguminous plants and used as animal pasture (Safrai,



337 2004, 98). Alternatively, dietary diversification may be responsible for the human-herbivore  
338 spacing. In the Roman period, domestic fowl and chicken especially gained economic importance in  
339 the Southern Levant and it has been suggested that egg consumption was considerable (Safrai 2004:  
340 101-102). Quantitative data from Ya‘amūn do not exist, but at nearby Pella, reliance on poultry,  
341 mostly chicken, increases sharply during the Byzantine period (McNicoll *et al.*, 1982, 110). The  
342 isotopic composition of eggs depends on the diet of the chicken (Hobson, 1995); however, because  
343 of their omnivorous feeding ecology, these can be significantly  $^{15}\text{N}$ -enriched over herbivores  
344 (Müldner and Richards, 2007).

345 There are numerous sources emphasizing the importance of fish and fish products in Roman and  
346 Byzantine Palestine (Garnsey, 1999, Lev-Tov, 2003, Marzano, 2013, Purcell, 1995, Van Neer and  
347 Parker, 2008). Based on the fishbone isotope data assembled here, there is little conclusive evidence  
348 that fish made any measurable contribution to Roman-Byzantine diet at Ya‘amūn. Lack of isotopic  
349 separation between freshwater fish and terrestrial animals makes it very difficult to convincingly  
350 demonstrate the consumption of freshwater fish, and although the  $\delta^{15}\text{N}$  values of the Late Antique  
351 humans could theoretically be explained by small-scale consumption of higher trophic level marine  
352 fish (such as the specimen of *Sciaenidae*, YMNfb88), Ya‘amūn’s inland location and the fact that  
353 YMNfb88 (which actually dates to the MBA) plots at the top end of  $\delta^{15}\text{N}$  values measured for  
354 Mediterranean fish to date (and is therefore not necessarily representative of any marine fish that  
355 reached the site), make significant consumption of marine protein at the site very unlikely .

356 The isotope data from Ya‘amūn are very similar to those from other Late Antique sites in the  
357 Levant (Al-Bashaireh and Al-Muheisen, 2011, Fuller *et al.*, 2012a, Gregoricka and Sheridan,  
358 2013),, suggesting again a similar subsistence base for the wider region. Unlike some other bone  
359 collagen data-sets (Bourbou *et al.*, 2011, Iacumin *et al.*, 1998, Thompson *et al.*, 2008), the sample  
360 from Ya‘amūn does not have any statistical outliers that would suggest that individuals moved from  
361 ecologically different regions, although the sample size is too small for any far-reaching

362 conclusions and carbon and nitrogen isotopes are not well suited to identify migrants in a  
363 population in any case.

364

## 365 **7. Conclusions**

366 Despite the small sample sizes which are, unfortunately, a common limitation of bone isotope  
367 investigations in arid and semi-arid regions, this study has established a number of clear trends. Of  
368 particular importance are differences in animal husbandry between the Middle and Late Bronze Age  
369 and Late Antiquity, which involved Bronze Age sheep/goats spending at least part of the year in  
370 arid or semi-arid regions, while Romano-Byzantine animals evidently stayed in the same  
371 phytogeographic zone. The reason behind this significant economic change may be the greater  
372 abundance of suitable fodder in the slightly wetter climate of Late Antiquity or else the need to keep  
373 the human workforce on-site to concentrate on other agricultural tasks, including the work-intensive  
374 viticulture (Horden and Purcell, 2000, 215). The cattle data from this period nevertheless show that  
375 the site was still connected to the drier regions to the East and South, possibly reflecting the move  
376 to expand agricultural production to the more marginal areas in the Byzantine period (Watson,  
377 2008). As expected based on the results of previous studies, the human diet in both periods was  
378 based almost exclusively on C<sub>3</sub>-based resources. While most isotopic differences between the  
379 human groups can be explained in terms of a baseline shift due to climatic change between the two  
380 periods, the Middle and Late Bronze Age inhabitants of Ya‘amūn may have consumed a greater  
381 proportion of leguminous plants, while the diet in Late Antiquity could have included a wider range  
382 of foods. Alternatively, their isotopic data may reflect the documented agricultural intensification in  
383 this period. Neither freshwater nor marine fish seem to have contributed significantly to the food  
384 intake of the sampled individuals. Overall, this study illustrates the need to analyse coeval faunal  
385 remains for human palaeodietary studies and confirms the great value of carbon and nitrogen stable

386 isotope analysis of herbivores for reconstructing environmental conditions in relation to changes in  
387 geographical location and climate.

## 388 **Acknowledgements**

389 This study, part of MS's PhD, was financed by Leverhulme Trust as part of the project "Water Life  
390 and Civilisation". Thanks go to Prof. Steven J. Mithen, University of Reading, for help and advice  
391 during PhD supervision. We are grateful to Prof. Mahmoud El-Najjar †, Dr Abdulla Al-Shorman,  
392 Dr Mohammad Al-Rousan and Dr Ammar Al-Obiedat of the Institute of Archaeology and  
393 Anthropology of Yarmouk University, Irbid, Jordan, to Prof Jerome Rose of the University of  
394 Arkansas, USA, for access to the skeletal material and for providing assistance and advice during  
395 sampling. We gratefully acknowledge the Department of Antiquities of Jordan as well as staff of  
396 Council for British Research in the Levant in Amman and especially Prof. Bill Finlayson for  
397 support during the 2006 fieldwork. Thanks go to Prof. Wim Van Neer, University of Leuven, for  
398 the identification of the fish vertebrae, Sarah Lambert-Gates (Reading) and Carlos H. Caracciolo  
399 (INGV, Bologna) for production of maps, and two anonymous reviewers for their constructive and  
400 helpful comments.

401

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**Table 1.** Descriptive statistics (group sizes, mean  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ , standard deviations and minimum and maximum values) for human and faunal samples from Ya'amūn

Group	n	mean $\delta^{13}\text{C}$ (‰) (min – max)	s.d.	mean $\delta^{15}\text{N}$ (‰) (min – max)	s.d.
MB and LB sheep/goats	6	-18.6 (-20.1 – -16.6)	1.4	8.5 (5.8 – 11.4)	1.9
LR/Byz sheep/goats	5	-19.3 (-20.1 – -19.6)	0.5	5.3 (4.0 – 6.4)	0.9
LR/Byz cattle	2	-18.8 – -15.6		5.4 – 9.7	
MB and LB humans	15	-18.8 (-19.4 – -18.3)	0.3	8.8 (7.4 – 9.8)	0.7
LR/Byz humans	17	-19.1 (-19.8 – -18.5)	0.3	8.1 (7.3 – 9.0)	0.6
Freshwater fish	3	-16.8 (-21.5 – -10.3)	5.8	6.9 (6.1 – 9.3)	2.0
Marine fish	2	-7.2 (-9.7 0 -4.7)	3.5	10.4 (8.2 – 12.6)	3.1

Ref: JASC14-754

Title: Diet and herding strategies in a changing environment: stable isotope analysis of Bronze Age and Late Antique skeletal remains from Ya'amūn, North Jordan

### Figure Legends

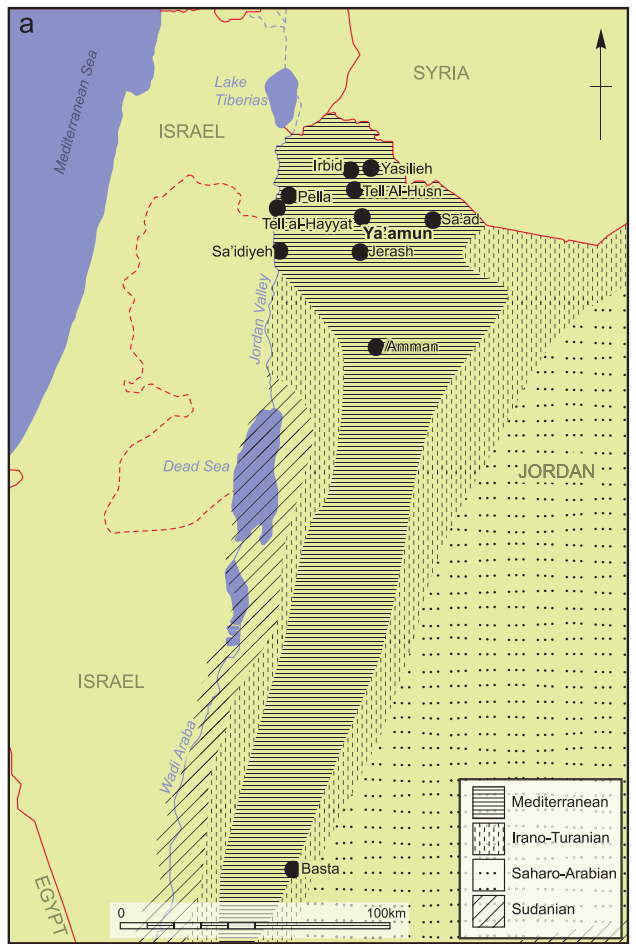
**Figure 1.** Map of Jordan with sites mentioned in the text superimposed on **(1.a)** the modern phytogeographic zones (based on data from Zohary 1973 and Al-Eisawi 1985, redrawn from Cordova 2007, Figure P.1, and Palmer 2013, Figure I.18) and **(1.b)** a rainfall map of modern Jordan (redrawn from Kennedy 2007, fig. 3.4a).

**Figure 2.** Carbon and nitrogen isotope data of Mid- and Late Bronze Age and Late Roman/Byzantine sheep/goats from Ya'amūn.  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of the Bronze Age sheep/goats are positively correlated (Pearson's  $r=0.87$ ,  $p=0.026$ ) and therefore consistent with varying consumption of plants from arid and semi-arid environments.

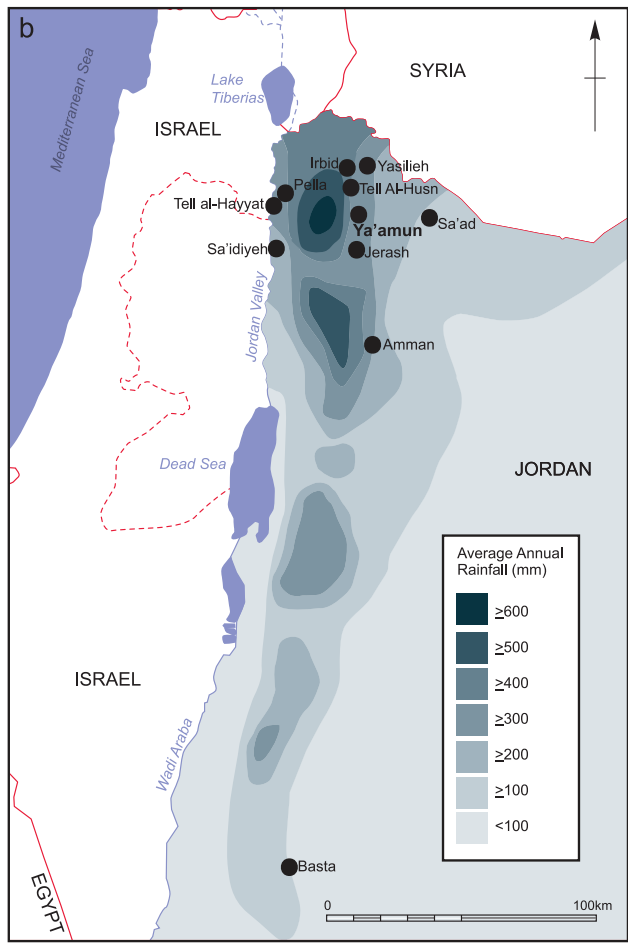
**Figure 3.** Carbon and nitrogen isotope data of Mid- and Late Bronze Age and Late Roman/Byzantine humans from Ya'amūn in comparison with mean values ( $\pm 1\text{sd}$ ) for sheep/goats from these time periods. The variation in human values to a large extent mirrors that observed in the fauna.

**Figure 4.** Carbon and nitrogen isotope data for humans (individual data) and sheep/goats (mean values  $\pm 1\text{sd}$ ) from Ya'amūn in comparison with  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values for marine (one specimen each of family *Scienidae* and *Mugilidae*) and freshwater fish (two specimens of *Tilapia* sp. and one of *Clarias* (catfish)) from the same site.

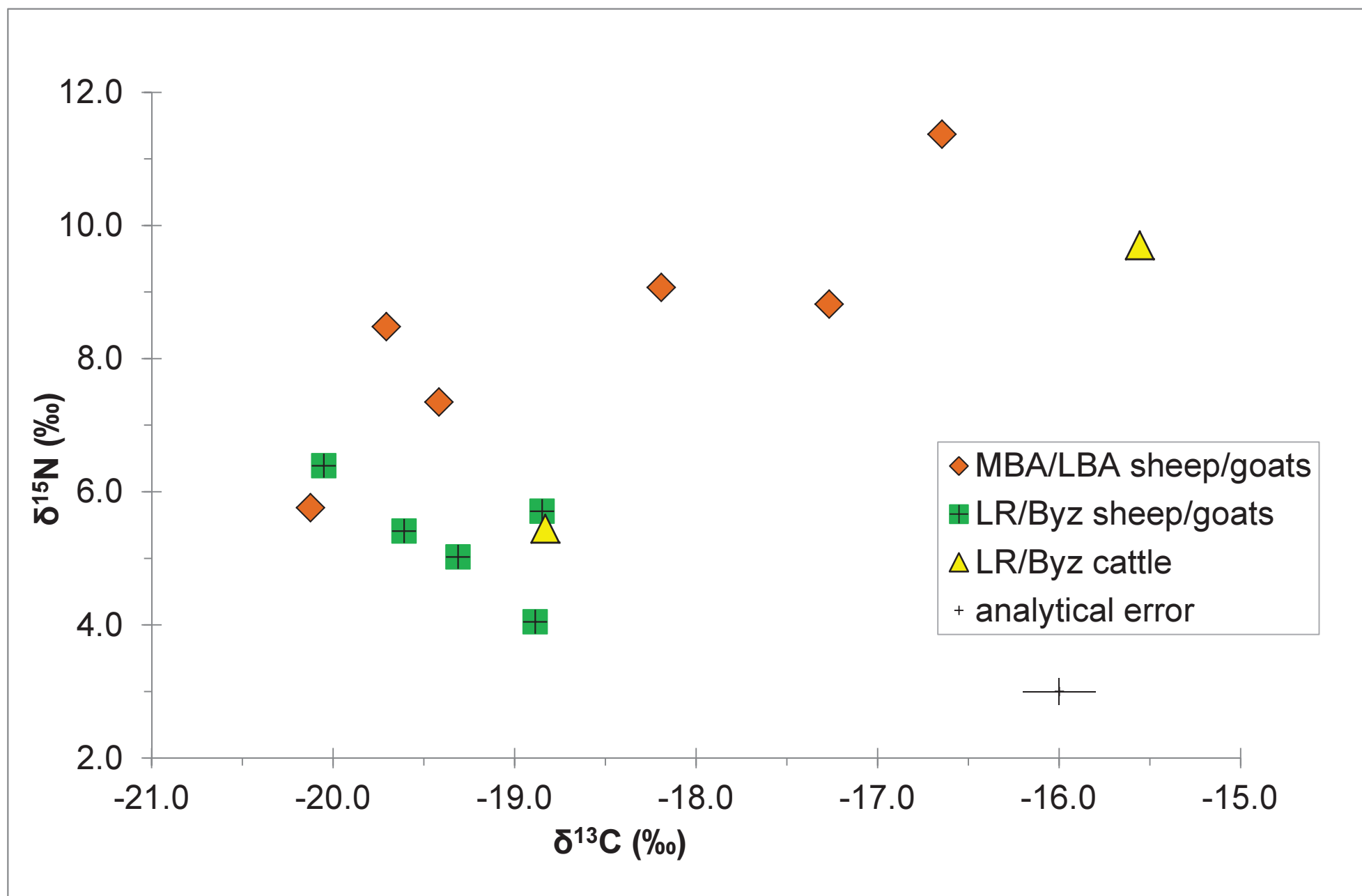
Figure



Figure

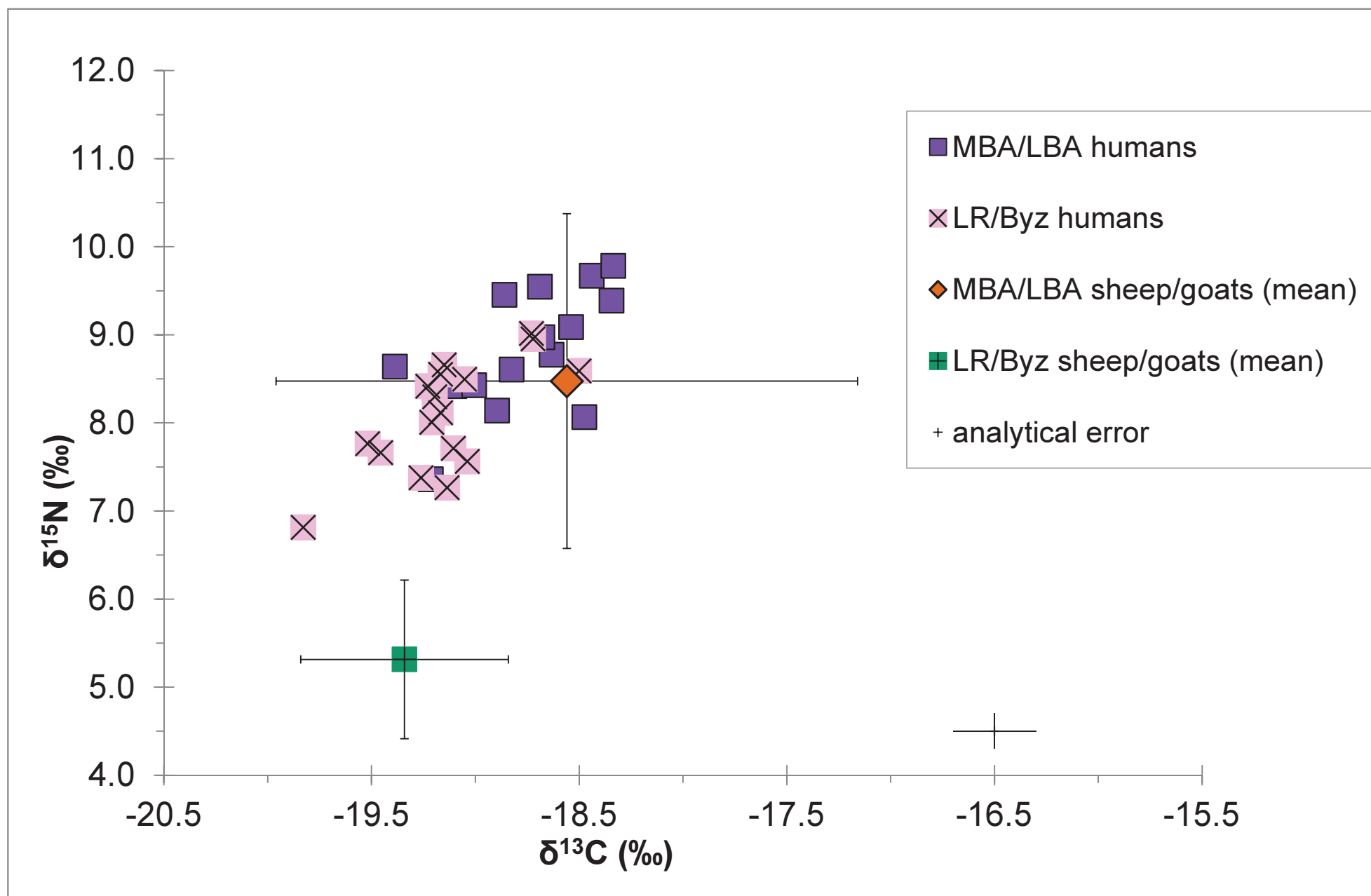


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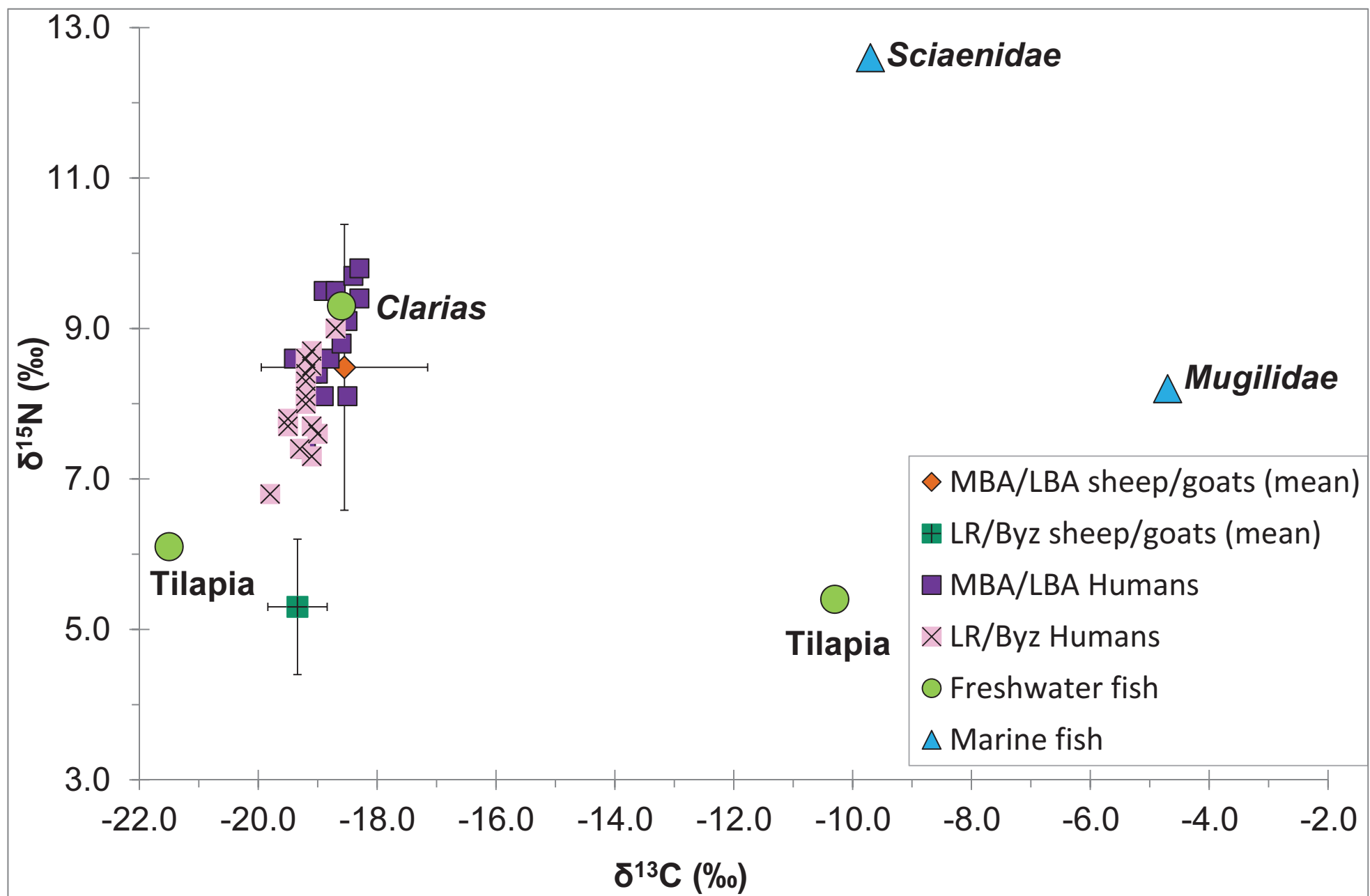




Figure



Figure



# 1 **Supplementary Information**

## 2 **Diet and herding strategies in a changing environment: stable isotope analysis of** 3 **Bronze Age and Late Antique skeletal remains from Ya'amūn, Jordan**

### 4 **Sample Preparation and Analytical Methods**

5 Cortical bone from the diaphysis of long bones, taken from areas devoid of any  
6 pathological lesions, was the preferred sampling material. Samples consisted of bone  
7 chunks weighing between 200 and 300 mg. All outer surfaces were abraded with the aid of  
8 a drill before collagen extraction was carried out following the Longin ((1971) method  
9 modified according to recommendations by Collins and Galley (1998). . Briefly, bone  
10 chunks were demineralised in 0.5 M in the fridge for several days, after which they were  
11 rinsed to neutrality with ultrapure water (Milli-Q®). The samples were then placed in a pH3  
12 HCl solution and gelatinised in a heater-block at 70 degrees C for 48 hours. Acid insoluble  
13 residues were removed with the aid of an Ezee®-filter (60-90µm, Elkay) and the  
14 remaining solutions was frozen and then freeze-dried for 48h. Aliquots of between 0.9 and  
15 1.1 mg of freeze-dried 'collagen' were weighed in duplicates into ultraclean tin capsules.

16 Carbon and nitrogen stable isotope compositions of samples were determined by analysis  
17 on a Europa Geo 20-20 Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS)  
18 interfaced with Sercon® elemental analyser (EA) in the School of Human and  
19 Environmental Sciences, University of Reading, UK. All  $\delta^{13}\text{C}$  values are expressed relative  
20 to Pee Dee Belemnite (V-PDB) and while the  $\delta^{15}\text{N}$  values are referred to atmospheric  
21 nitrogen (AIR). The analytical error was calculated from repeat analysis of internal collagen  
22 standards included in each run and was determined at  $\pm 0.2\%$  (1sd) or better for  $\delta^{13}\text{C}$ ,  
23 and  $\delta^{15}\text{N}$  measurements. Internal working standards which were calibrated to  
24 internationally certified reference materials included the amino acid methionine (Elemental  
25 Microanalysis/MethR), powdered Bovine Liver Standard (NIST1577a/BLS) and a batch of  
26 pork gelatine prepared at the Reading stable isotope laboratory ("Reading Pork  
27 Gelatine"/RPG).

28 Collagen samples were considered of acceptable quality when having an atomic C:N ratio  
29 between 2.9 and 3.6, %C  $\geq$  13% and %N  $\geq$  4.8% (Ambrose, 1990, DeNiro, 1985).  
30 Samples that yielded less than 1% collagen were still regarded as acceptable if they

31 fulfilled these criteria and if their  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  ratios were not unusual within the  
32 population context (van Klinken 1999). Inferential statistics were computed with SPSS  
33 v.19.

34

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44

45 **Table S1.** Carbon and nitrogen stable isotope data and collagen quality indicators of  
 46 faunal bone samples from Ya'amūn. Archaeological dates are abbreviated as follows:  
 47 MBA=Middle Bronze Age; LBA=Late Bronze Age; LR/Byz=Late Roman/Byzantine. Nil  
 48 refers to samples which yielded no collagen for analysis.

Species	Sample Code	Date	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	%Coll
<i>Bos</i>	YMN fb 084	MBA						Nil
Sheep/Goat	YMN fb 085	MBA						Nil
Sheep/Goat	YMN fb 086	MBA	-19.7	8.5	40.3	14.0	3.4	1.3
Sheep/Goat	YMN fb 087	MBA	-16.6	11.4	19.5	6.8	3.4	2.6
Fish ( <i>Sciaenidae</i> ).	YMN fb 088	MBA	-9.7	12.6	40.0	14.3	3.3	6.6
Sheep/Goat	YMN fb 089	MBA	-19.4	7.3	41.1	13.8	3.5	0.8
Sheep/Goat	YMN fb 090	MBA						Nil
Sheep/Goat	YMN fb 074	LBA						Nil
Sheep/Goat	YMN fb 075	LBA	-20.1	5.8	42.8	15.0	3.3	3.1
Sheep/Goat	YMN fb 076	LBA	-17.3	8.8	42.8	15.2	3.3	2.7
Sheep/Goat	YMN fb 077	LBA	-18.2	9.1	42.6	15.1	3.3	7.2
Sheep/Goat	YMN fb 078	LBA						Nil
Sheep/Goat	YMN fb 092	LR/Byz	-19.3	5.0	41.6	15.0	3.2	9.0
Sheep/Goat	YMN T fb 093	LR/Byz	-18.8	5.7	39.0	14.2	3.2	12.0
<i>Bos</i>	YMN T fb 094	LR/Byz	-18.8	5.4	42.3	15.2	3.3	3.4
<i>Bos</i>	YMN T fb 095	LR/Byz	-15.6	9.7	44.1	16.0	3.2	16.0
Sheep/Goat	YMN T fb 096	LR/Byz	-20.1	6.4	38.0	13.3	3.3	4.1
Sheep/Goat	YMN T fb 097*	LR/Byz	-18.9	4.0	43.6	16.0	3.2	18.2
Sheep/Goat	YMN T fb 098	LR/Byz	-19.6	5.4	41.1	14.7	3.3	9.2
Fish ( <i>Mugilidae</i> )	YMN T fb 099	LR/Byz	-4.7	8.2	43.1	15.8	3.2	12.0
Fish ( <i>Tilapia</i> sp.)	YMN T fb 100	LR/Byz	-21.5	6.1	43.2	15.7	3.2	10.0
Fish ( <i>Tilapia</i> sp.)	YMN T fb 101	LR/Byz	-10.3	5.4	42.4	15.5	3.2	9.4
Fish ( <i>Clariidae</i> )	YMN T fb 102	LR/Byz	-18.6	9.3	41.2	14.9	3.2	6.0

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51 **Table S2.** Carbon and nitrogen stable isotope data and collagen quality indicators of  
 52 human bone samples from Ya'amūn. Archaeological dates are abbreviated as follows:  
 53 MBA=Middle Bronze Age; LBA=Late Bronze Age; LR=Late Roman; Byz= Byzantine. Nil  
 54 refers to samples which yielded no collagen for analysis.

Sample Code	Date	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	%Coll
YMN hb 001	MBA	-19.4	8.6	40.4	14.0	3.4	0.9
YMN hb 002	MBA	-19.1	8.4	42.2	14.8	3.3	4.0
YMN hb 003	MBA	-18.9	9.5	42.2	14.7	3.3	2.0
YMN hb 004	MBA	-19.2	7.4	41.5	13.9	3.5	0.6
YMN hb 005	MBA						Nil
YMN hb 006	MBA	-19.0	8.4	41.6	13.5	3.6	1.3
YMN hb 007	MBA						Nil
YMN hb 008	MBA						Nil
YMN hb 009	MBA	-18.5	9.1	41.0	14.6	3.3	4.3
YMN hb 010	MBA	-18.3	9.4	43.4	15.6	3.2	9.3
YMN hb 011	MBA	-18.4	9.7	43.8	15.7	3.3	7.5
YMN hb 012	MBA						Nil
YMN hb 013	MBA	-18.6	8.8	42.9	15.4	3.3	9.0
YMN hb 014	MBA	-18.9	8.1	43.3	15.7	3.2	10.0
YMN hb 015	MBA	-18.3	9.8	42.4	15.3	3.2	5.1
YMN hb 016	MBA	-18.8	8.6	43.0	15.7	3.2	14.5
YMN hb 017	LBA						Nil
YMN hb 018	LBA						Nil
YMN hb 019	LBA	-18.7	9.0	42.8	15.4	3.2	6.0
YMN hb 020	LBA						Nil
YMN hb 021	LBA	-18.7	9.5	42.0	15.1	3.2	2.8
YMN hb 022	LBA	-18.5	8.1	39.0	13.8	3.3	4.0
YMN hb 023	LR						Nil
YMN hb 024	LR	-19.1	8.5	41.4	15.1	3.2	10.0
YMN hb 025	LR	-18.7	9.0	42.8	15.3	3.3	10.0
YMN hb 026	LR	-19.5	7.7	40.9	14.1	3.4	1.3
YMN hb 027*	Byz	-18.5	8.6	43.0	15.5	3.2	17.0
YMN hb 028	Byz	-19.1	7.3	38.5	13.5	3.3	3.5
YMN hb 029	Byz	-19.3	7.4	39.1	13.6	3.4	3.6
YMN hb 030	Byz	-19.2	8.0	35.9	12.5	3.3	2.6
YMN hb 031	Byz	-19.8	6.8	42.0	14.9	3.3	3.6
YMN hb 032	Byz	-19.1	7.7	43.4	15.3	3.3	3.3
YMN hb 033	Byz	-19.5	7.8	28.9	9.9	3.4	3.7
YMN hb 034	LR/Byz	-19.0	7.6	33.0	11.7	3.3	5.8
YMN hb 035	LR/Byz	-19.2	8.6	38.3	13.5	3.3	7.2
YMN hb 036	LR/Byz						Nil
YMN hb 037	LR/Byz						Nil
YMN hb 038	LR/Byz	-19.2	8.3	43.0	15.0	3.4	6.0
YMN hb 039	LR/Byz	-19.2	8.1	41.6	14.3	3.4	4.2
YMN hb 040	LR/Byz						Nil
YMN hb 041	LR/Byz						Nil
YMN hb 042	LR/Byz						Nil
YMN hb 043	LR/Byz	-18.7	9.0	43.4	15.6	3.2	6.8
YMN hb 044*	LR/Byz	-19.2	8.4	43.7	15.7	3.2	19.5
YMN hb 045	LR/Byz	-19.1	8.7	42.8	15.1	3.3	11.5

