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# Capturing Roman dietary variability in the catastrophic death assemblage at Herculaneum

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## Abstract

Here we present a comparative study of stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotope data from 81 individuals from the catastrophic death assemblage at Herculaneum (79 AD) and compare these with the attritional sites of Velia (Salerno, Italy, 1<sup>st</sup>-2<sup>nd</sup> century AD) and Isola Sacra (Rome, Italy, 1<sup>st</sup>-2<sup>nd</sup> century AD). The instantaneous deposition of the Herculaneum assemblage highlights some interesting differences in our contextual and methodological understanding of stable dietary isotopes, suggesting that isotopic variation between sites may sometimes be a result of greater temporal variability rather than truly comparable differences. Our results suggest that the people of Herculaneum obtained a relatively small proportion (ca. 30%) of their dietary carbon from marine foods; the majority originating from terrestrial foodstuffs of a similar carbon isotopic composition, most likely cereals. Also observed is a generally greater dietary isotopic enrichment in male individuals than females. We infer that males had greater access to fish which may be reflective, in part, of the sociodemographic framework characteristic of Roman society. Finally, we highlight the methodological challenges which may be faced when undertaking comparisons of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data between the various age-related strata of a population, particularly due to the slow and variable rate of collagen turnover.

Keywords: Herculaneum; stable isotopes; palaeodiet; Vesuvius

## 1.1 Introduction

The health and economic 'well-being' of the Roman world is a fundamental benchmark in the historic investigation of past civilisations. Although the study of the Roman productive economy is extensive, our knowledge regarding the distribution of wealth and differences in living conditions in Roman society is limited to partial and incomplete records (Garnsey and Saller, 2015). We do not yet know how food was distributed to different elements of the population, between households, villages or towns. Historical accounts (Rackham, 1967; Edwards, 2001; Wolf, 2010) and archaeological evidence from animal and plant remains

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43 (Meyer, 1980; Pagano, 1994; Reese, 2002; Rowan, 2014; Robinson and Rowan, 2015)  
44 provide specific information regarding the types of foods that were eaten but lack the  
45 resolution required to quantify dietary content, or to study dietary variability within societies.  
46 Such information is crucial if we are to make meaningful comparisons between Roman and  
47 other pre-modern and developing societies, and to clarify relationships between social  
48 status, health and nutrition.

49

50 Stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotope analysis of bone collagen offers a direct  
51 approach to the inter- and intra-population study of ancient diet. Isotopic signals represent a  
52 direct measure of an individual's average dietary intake during the period of bone collagen  
53 formation. These analyses are particularly useful for discriminating diets of coastal  
54 inhabitants with access to mixed marine and terrestrial diets, and where the major dietary  
55 sources (e.g. marine fish, terrestrial herbivores, terrestrial omnivores and cereal grains) have  
56 distinct isotope values. So far, the analyses of over 500 individuals from Roman Imperial  
57 period necropolises in southern Italy have succeeded in identifying relative isotopic  
58 differences within and between assemblages, attributed to differences in occupation, age  
59 and sex, and mainly relating to the differential consumption of marine foods (Prowse *et al.*,  
60 2004; Craig *et al.*, 2009; Killgrove and Tykot, 2013; Killgrove and Tykot, in press).  
61 Nevertheless, the analysis of diet in such attritional death assemblages is heavily burdened  
62 by methodological and interpretative limitations. Unlike census data, skeletal assemblages  
63 from burial grounds are palimpsests that gradually accumulate over time, and their fidelity to  
64 any living population is undermined by both selective burial and selective mortality (Wood *et al.*,  
65 1992; Roberts and Grauer, 2001; Jackes, 2011; DeWitte and Stojanowski, 2015). For  
66 example, individuals who were afforded cremation, a common Roman funerary custom,  
67 cannot be studied, whilst frail individuals who succumbed to disease are likely to be over-  
68 represented in the younger age classes (Wood *et al.*, 1992).

69

70 In studying stable isotopic data from a sample of 81 individuals from the catastrophic death  
71 assemblage at Herculaneum (Bisel, 1991; Capasso and Domenicantonio, 1998; Capasso  
72 and Capasso, 1999; Capasso, 2000; Mastrolorenzo *et al.*, 2001; Mastrolorenzo *et al.*, 2010;  
73 Petrone, 2011), we hope to circumvent these problems and derive a clearer picture of  
74 dietary variability in at least one Roman town. All were victims of the 79 AD eruption of  
75 Vesuvius and were discovered within 9 *fornici* (stone vaults) running adjacent to the seafront  
76 (Fattore *et al.*, 2012). The stable isotope data for 72 individuals were originally reported in  
77 Craig *et al.* (2013) but here we investigate these data with respect to new osteological  
78 information regarding the age and sex of the skeletons. Notably, this revision identified one  
79 of the 72 individuals (F8I10) as a juvenile. In addition, we also report new isotopic data from  
80 9 infants and juveniles (<20 years of age). Albeit a modest sample of a small Imperial  
81 coastal town of ca. 4-5,000 residents (Wallace-Hadrill, 2011), the assemblage contains a  
82 broadly equal mixture of adult males and females, with juveniles and infants also  
83 represented (Capasso, 2000; Mastrolorenzo *et al.*, 2001). Whilst some selectivity in those  
84 sheltering in the vaults is to be expected, the assemblage offers a rare glimpse of  
85 contemporary Roman life, where sudden and collective death negated the selective biases  
86 usually faced in osteoarchaeological analysis. Therefore, we are able for the first time to  
87 quantify the differential access to foods within an ancient 'living' population.

## 88 1.2 Methods

89 Collagen for the new 9 samples was extracted from bone and analysed by EA-IRMS exactly  
90 as described previously (Craig *et al.*, 2013). In the majority of for both these samples and  
91 those presented in Craig *et al.* (2013), rib samples were chosen (Craig *et al.* 2013; see  
92 Supporting Information, Table 1) and any samples showing signs of pathological change  
93 were excluded. Briefly, bone samples (0.5-1g) were coarsely ground and demineralised (0.6  
94 M HCl, 4°C, 3-12 days), samples were rinsed with distilled water and then gelatinised (pH3  
95 [0.001M] HCl, 80°C, 48h). The supernatant containing the collagen was filtered (30 kDa,  
96 Amicon® Ultra-4 Centrifugal Filter Units, Millipore, Billerica, MA, USA), frozen, and  
97 lyophilised. Collagen samples (1mg) were analysed in duplicate or triplicate by EA/IRMS in a  
98 Sercon GSL analyser coupled to a Sercon 20-22 Mass Spectrometer (Sercon, Crewe, UK)  
99 at the University of York, or a Roboprep Combustion Device coupled to a Europa 20-20  
100 Mass Spectrometer (PDZ-Europa, Crewe, UK). The analytical error, calculated from  
101 repeated measurements of each sample and measurements of the bovine control from  
102 multiple extracts, was <0.2‰ (1σ). Accuracy was determined by measurements of  
103 international standard reference materials (IAEA 600, IAEA N2, IA Cane) within each  
104 analytical run, with the error being less than <0.5‰ in all instances. The difference in the  
105 <sup>15</sup>N/<sup>14</sup>N ratio between the sample and the internationally defined standard AIR (atmospheric  
106 air) in ‰ units is referred to as δ<sup>15</sup>N, and δ<sup>13</sup>C refers to the difference in <sup>13</sup>C/<sup>12</sup>C ratio  
107 between the sample and the internationally defined standard, PDB (Vienna Peedee  
108 Belemnite Limestone). The reported ratios are calculated using the equation: δx = ((R<sub>sample</sub> -  
109 R<sub>standard</sub>)/R<sub>standard</sub>) x 1000.

110  
111 For Herculaneum, the <sup>14</sup>C offset attributable to the marine reservoir effect was estimated for  
112 each sample using the following regression equation derived from radiocarbon dating and  
113 stable isotope analysis of 9 samples (Craig *et al.*, 2013):

114  
115 (1)  $y = 34.3 - 300x$ ,  $R^2 = 9.1$  where  $y = ^{14}\text{C}$  offset (years) and  $x = \delta^{15}\text{N}$  value (‰).

116  
117 These 9 individuals are a sub-sample of the 81 individuals analysed for δ<sup>13</sup>C and δ<sup>15</sup>N in the  
118 current study.

119  
120 The calculated <sup>14</sup>C offset from the above equation was used to estimate the % of total  
121 carbon derived from a marine source, assuming a maximum reservoir age of 390 years  
122 corresponding to 100% marine derived carbon. The % of marine protein contribution to  
123 collagen was derived through linear interpolation of values between the terrestrial endpoint  
124 (+7.2‰) and marine endpoint (+16‰). The latter were derived from measurements of  
125 contemporary herbivore and marine fish values, using similar assumptions as previously  
126 reported (Craig *et al.*, 2013). All statistical analysis was carried out using R version 3.1.2.

127  
128 The human osteological material was analysed according to the common standards reported  
129 in the literature (Krogman and İşcan, 1986; Buikstra and Ubelaker, 1994; White and Folkens,  
130 2005). Sex determination in the adults was obtained by the application of the visual  
131 assessment of the morphological traits of skull and pelvis (Ferembach *et al.*, 1980; White  
132 and Folkens, 2005). Age at death was determined using multiple age indicators. For adult  
133 individuals, methods included: degenerative changes of the pubic symphysis (Todd, 1921),  
134 the auricular surface of the innominate (Buikstra and Ubelaker, 1994), and the sternal ends

135 of ribs (Işcan *et al.*, 1984); ecto- and endo-cranial suture closure (Buikstra and Ubelaker,  
136 1994). For individuals still growing at the time of death the following criteria were applied:  
137 stages of epiphyseal fusion (Scheuer *et al.*, 2010), long bone dimensions (Scheuer *et al.*,  
138 2010), and the stages of formation and eruption of teeth (AlQahtani *et al.*, 2010). The  
139 analyses were independently performed by three observers (PP, LF, AS,) and cases of  
140 discrepancy were resolved by a fourth joint and consensual analysis (on the reliability of the  
141 age-at-death assessment see (Baccino *et al.*, 1999; Garvin and Passalacqua, 2012). The  
142 extraordinary preservation state of the skeletal and dental material allowed for the age at  
143 death to be determined by 5 year intervals for subadults and 10 year intervals for adult  
144 individuals (the last age class being 50+), thus permitting comparison with almost  
145 contemporaneous central Italian skeletal series (Prowse *et al.*, 2004; Prowse *et al.*, 2005;  
146 FitzGerald *et al.*, 2006; Craig *et al.*, 2009; Crowe *et al.*, 2010; Petrone *et al.*, 2011).  
147 The Herculaneum sample set reported in this paper is composed of 81 individuals: 28  
148 females, 37 males, 6 unsexed individuals older than 15 years and 10 individuals (<15 years)  
149 which were unsexed, see Supplementary Information, Table 1.  
150 For the dietary reconstruction, we included the biological sub-adults (age 15-20, 5 males, 2  
151 females, and 4 unsexed) within the analysis of the adult individuals on the grounds that they  
152 probably ate an adult diet, being classed 'social' adults in accordance with the trend of  
153 traditional Roman life (Treggiari, 1993).

154

## 155 **1.3 Results and Discussion**

### 156 **1.3.1. Dietary variation at Herculaneum and other coastal Roman sites**

157 The carbon and nitrogen stable isotope data for the Herculaneum population are reported in  
158 Supporting Information, Table 1. These include all the data reported in Craig *et al.* (2013)  
159 plus those from an additional 9 infants and juveniles. Overall, the isotope data for all  
160 individuals >15 years fall within the range of similar age cohorts from other coastal Imperial  
161 necropolises (Fig. 2). These are Isola Sacra (Prowse *et al.*, 2004; Crowe *et al.*, 2010), the  
162 cemetery that served Portus Romae- the gateway to Rome, and Velia- a small coastal town  
163 south of Naples (Craig *et al.*, 2009) (Fig. 1). The  $\delta^{13}\text{C}$  values at each of the three sites have  
164 comparable ranges (Herculaneum = -18.2‰ to -20.2‰; Isola Sacra = -17.8‰ to -19.5‰;  
165 Velia = -18.7‰ to -20.0‰) but the variances are significantly different between sites (Fligner-  
166 Killeen test of homogeneity of variances;  $\chi^2 = 6.8$ ,  $p = 0.03$ ).



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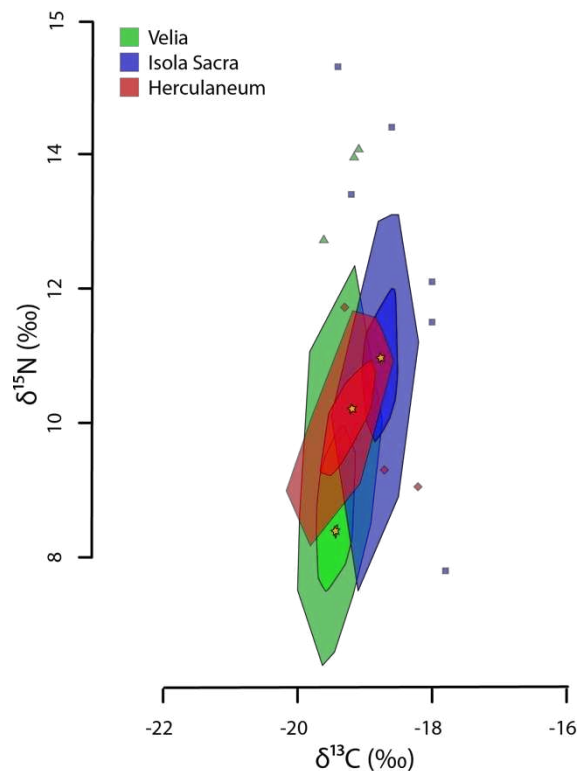
**Fig. 1: Map showing approximate locations of Italian Roman Imperial period sites referred to in the text (after Craig *et al.* (2013)).**

173 It is noticeable, however, that that the  $\delta^{15}\text{N}$  values for Herculaneum show a narrower range  
174 (8.2‰ to 11.7‰) than for Isola Sacra (7.5‰ to 15.3‰) or Velia (6.4‰ to 14.1‰), despite  
175 similar sample sizes (Velia = 117; Isola Sacra = 94; Herculaneum = 71). Conversely, the  
176 variances within samples are not significantly different (Fligner-Killeen test of homogeneity of  
177 variances;  $\chi^2 = 3.4$ ,  $p = 0.18$ ). The bagplots (Fig. 2 (Rousseeuw *et al.*, 1999)) clearly show  
178 that Herculaneum has an "intermediate" position between the two other coastal sites both for  
179  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ , and a much narrower distribution of  $\delta^{15}\text{N}$  values. One explanation for the  
180 relatively reduced dietary variation at Herculaneum compared to Isola Sacra and Velia is the  
181 nature of the assemblage formations. As the latter are individuals from cemeteries that were  
182 used for many generations (ca. 150 years for Velia and ca. 300 years for Isola Sacra),  
183 greater isotopic variation may simply reflect greater dietary variation through time, rather  
184 than real differences in the diet of the living populations, as is commonly assumed when  
185 such comparisons are made.

186  
187 To test for inter-site differences in  $\delta^{15}\text{N}$ , a robust ANOVA model was used. As diet is  
188 significantly affected by sex in each of these assemblages (see section 1.3.2.), it was  
189 particularly important to examine whether differences in the demographic profiles are a more  
190 likely explanation for the amplitude of isotopic variation between sites. The  $\delta^{15}\text{N}$  values are  
191 significantly different by site ( $F = 129.4$ ,  $p = <0.001$ ) as expected but not when the interaction  
192 between sex and site is considered ( $F = 0.1$ ,  $p = 0.89$ ). Therefore, the distribution of  $\delta^{15}\text{N}$   
193 values genuinely reflects greater dietary variation at the attritional assemblages, compared  
194 to Herculaneum. Interestingly the core distributions, containing 25% to 75% of the  $\delta^{15}\text{N}$  data  
195 (Fig. 2), at each assemblage are comparable in terms of amplitude of variance. The main

196 difference between the sites is that Velia and Isola Sacra have a greater number of outliers,  
197 particularly individuals with high marine protein diets (i.e. high  $\delta^{15}\text{N}$  values).

198  
199 Finally, the amplitude of variance in  $\delta^{15}\text{N}$  between the sites is not easily explained by greater  
200 absolute differences in dietary end-points (plants and fish) as discussed previously (Craig *et al.*,  
201 2009), although temporal variation in these, particularly changes in location of grain  
202 supply, would be interesting to check. The consumption of leguminous vegetables, thought  
203 to be integral to the Roman diet (Garnsey, 1999) and with ample evidence from Vesuvian  
204 cities (Meyer, 1980; Wolf, 2010), should also be explored. These may have a large effect on  
205 the isotopic endpoints since they are relatively depleted in  $^{15}\text{N}$ . Finally, the presence in the  
206 Velia assemblage of a specific subset of individuals, possibly fishermen, has been observed  
207 (Crowe *et al.*, 2010) and contributes to the broad range of  $\delta^{15}\text{N}$  for this site.  
208



209  
210  
211 **Fig. 2: Bagplot of three Roman Imperial period mortuary assemblages.** Comparison of human  
212 stable isotope data between Velia (left) and Isola Sacra (middle) by means of bagplots. A bagplot is a  
213 bivariate generalization of the boxplot. The central darker shaded area contains 50% of all data  
214 points. The outer lighter shaded area is three times the area of the central part and is fenced by a line  
215 connecting data points that lie on the periphery of this area. Points outside the fence are considered  
216 outliers. Medians are represented with a gold star.

### 217 1.3.2. Variation by sex

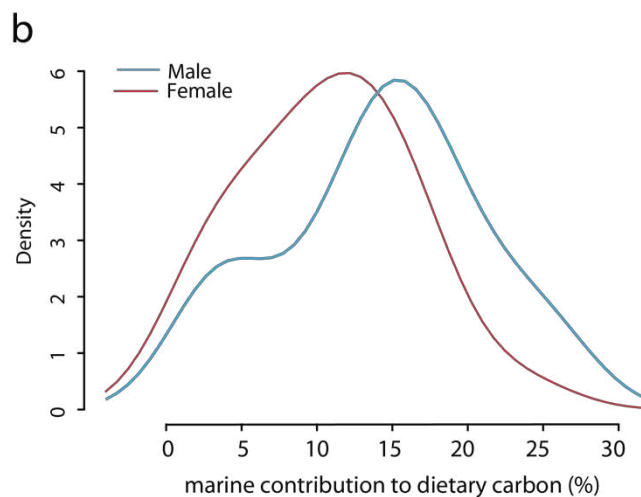
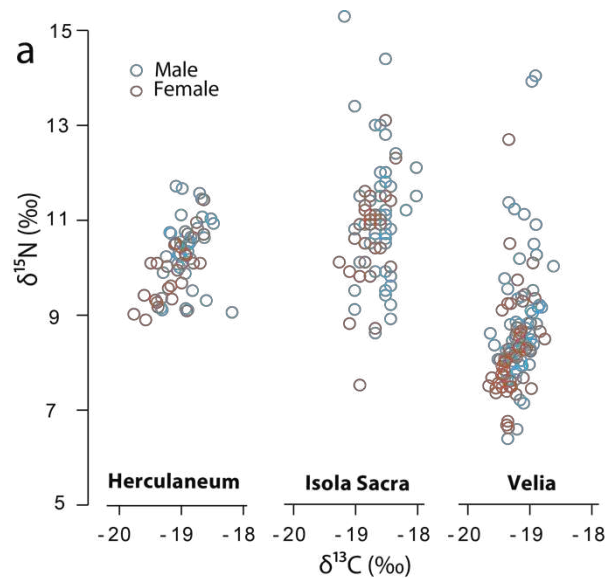
218 The distribution of  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  is significantly different between the sexes at Herculaneum  
219 (Kruskal-Wallis,  $\chi^2 = 4.6$ ,  $p = 0.03$  and  $\chi^2 = 5.1$ ,  $p = 0.02$  for each isotope, respectively) with  
220 males typically enriched in  $^{15}\text{N}$  and  $^{13}\text{C}$  compared to females (Fig. 3a). From these data, it is  
221 proposed that males consumed more fish with relatively elevated  $\delta^{15}\text{N}$  values. This is not to  
222 suggest that other low trophic level species were not consumed at Herculaneum, either fresh  
223 or as commodities such as garum. Indeed there are ample remains of small fish such as

224 sardine, anchovy, and marine shellfish from sewer deposits (Rowan, 2014) but these are  
225 less likely to be distinguished isotopically.

226

227 At Herculaneum, since all the individuals died simultaneously (Mastrolorenzo *et al.*, 2001),  
228 we can exploit differences in individual radiocarbon dates to independently quantify marine  
229 food consumption with much more certainty. At this site it has been previously shown that  
230 both carbon and nitrogen isotopes in human bone collagen are positively linearly correlated  
231 with the amount of 'old' carbon derived from the marine reservoir (Craig *et al.*, 2013). On this  
232 basis, it is estimated that across the Herculaneum sample a relatively small proportion (0-  
233 30%) of the total carbon in bone collagen, broadly equivalent to the weight % or calorific  
234 contribution to the diet, was derived from marine foods (Craig *et al.*, 2013). Given their richer  
235 protein content, marine foods make a much greater contribution to total dietary protein  
236 (nitrogen) which at Herculaneum is estimated to range between 20-50% (Craig *et al.*, 2013).  
237 These estimates are also supported by the application of a Bayesian mixing model, which  
238 takes into account the macronutrient composition of different food groups (Fernandes,  
239 2015).

240



241



242 **Fig 3: Stable isotope measurements of human remains from Herculaneum.** a.) - compared with  
243 Isola Sacra and Velia; b.) - showing the Kernel density plot of all adults from Herculaneum by sex (F =  
244 28; M = 37) against the estimation of % marine carbon to total dietary carbon.

245  
246

247 Apart from fish, the remainder of the diet at Herculaneum - at least 70% by weight - was  
248 made up of terrestrial foodstuffs of similar isotopic composition and of substantially less  
249 protein content than fish. Although other low-protein terrestrial foods, even fatty meats or  
250 legumes, cannot be ruled out (Fernandes *et al.*, 2014), the most likely contenders are  
251 cereals. Carbonized remains of cereals, mainly naked wheats and barley, have been found  
252 in abundance at Herculaneum and in the Villa dei Papiri nearby (Meyer, 1988; Ciarallo,  
253 1994; Pagano, 1994). A cache of 117 wooden writing tablets (the 'Murecine Tablets') found  
254 in a wicker basket just outside the walls of Pompeii and dating from the mid-first century (29-  
255 61 AD) reveals that 'Alexandrian wheat' was stored in large quantities in warehouses at  
256 Puteoli (Camodeca, 1999; Wolf, 2010). Overall, the high consumption of cereals with a  
257 relatively low protein concentration, and variable contribution of marine foods, explains the  
258 narrow range of  $\delta^{13}\text{C}$  values compared with  $\delta^{15}\text{N}$  values observed at Herculaneum and other  
259 Italian Roman Imperial period coastal sites (Fig. 3a) (Craig *et al.*, 2013).

260

261 The observed isotopic differences between the sexes at Herculaneum could simply be a  
262 matter of biology; the calorific requirements of males are known to be greater than those of  
263 females, and the undertaking of hard labour would undoubtedly exacerbate such needs  
264 leading to quantitative and qualitative dietary discrepancies. However, it is terrestrial  
265 products - mainly cereals - that provided the majority of calories regardless of sex, so this is  
266 less likely. Rather, it is the consumption of high trophic level marine fish that isotopically  
267 distinguishes males from females. In Figure 3b we have used the  $\delta^{15}\text{N}$  to indicate the %  
268 contribution of marine foods to dietary carbon (an approximation to their weight contribution  
269 to total diet) using equation 1 (above). The distributions (Fig. 3b) show that a small  
270 proportion of the males obtained a slightly greater % of their total diet from marine foods.  
271 The differences between males and females with respect to marine consumption is great  
272 (typically <5% contribution to total diet) but the effect on their  $\delta^{15}\text{N}$  values is much more  
273 pronounced, since fish makes a disproportional contribution to dietary protein.

274

275 It is reasonable to suppose that occupation is a key variable which determines these sex-  
276 related dietary differences. Men had primary access to marine foods in as much as fishing  
277 and trade in fish products were male-dominated activities. In general, the uneven distribution  
278 of power, which in a traditional society lay with males, and other social factors, would have  
279 played a part in permitting or restricting access to fish, both within the families of fishermen,  
280 and in the wider community (Garnsey 1999).

281

### 282 **1.3.3. Variation by Age**

283 When the sample is subdivided into specific age classes (15–20, 20–30, 30–40, 40–50, 50+  
284 years) there are no significant differences in  $\delta^{15}\text{N}$  values (Kruskal-Wallis  $\chi^2 = 7.0$ ,  $p = 0.13$ )  
285 or in  $\delta^{13}\text{C}$  values (Kruskal-Wallis  $\chi^2 = 6.4$ ,  $p = 0.17$ ). If the data are first disaggregated by sex  
286 and then compared by age, there are no significant differences between males and females  
287 in any of the age classes, or between males and females of different age classes (Robust

288 ANOVA  $\delta^{15}\text{N}$  interaction between age classes and sex  $F = 2.6$ ,  $p = 0.05$ ; Robust ANOVA  
289  $\delta^{13}\text{C}$  interaction between age classes and sex  $F = 1.1$ ,  $p = 0.37$ ). Overall, the intra-  
290 population stable isotopic variation at Herculaneum is related to sex but seems to be less  
291 dependent on an individual's age at death. However,  $\delta^{15}\text{N}$  values are significantly different  
292 between adults less than 30 years old (i.e. 15-30) compared with those older than 30 years  
293 (Wilcoxon rank sum test with continuity correction  $W = 385.5$ ,  $p = 0.04$ ). When testing for the  
294 interaction with sex within these age classes, the robust ANOVA shows no significant  
295 interaction for  $\delta^{15}\text{N}$  ( $F = 2.6$ ,  $p = 0.05$ ). Boxplots in Figure 4 show that older males at  
296 Herculaneum tended to have diets richer in marine foods. Conversely, females and younger  
297 males have diets more similar to each other. There are no significant differences in  $\delta^{13}\text{C}$   
298 values between these broader (15-30, 30+ years) age ranges (Wilcoxon rank sum test with  
299 continuity correction  $W = 469.5$ ,  $p = 0.30$ ).

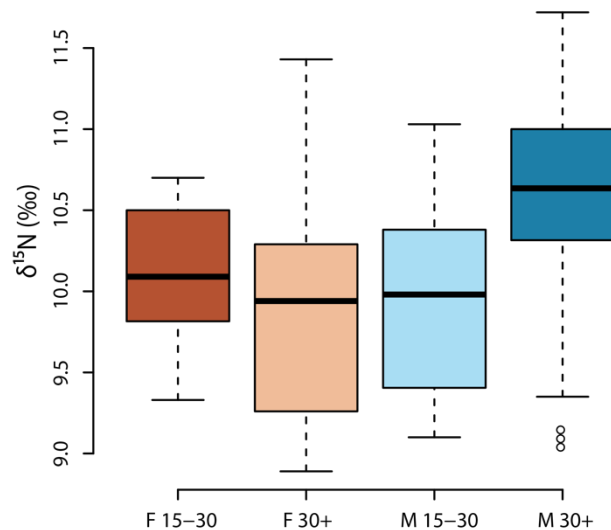
300

301 Certainly, we would expect some age and sex related differences at Herculaneum. By 30  
302 years of age, most men might be supposed to have received a boost in their disposable  
303 income, allowing access to greater quantities of more expensive commodities such as fish.  
304 By 30 years old most men would have entered into their first marriage (Saller, 1996; Aldrete,  
305 2008; Garnsey and Saller, 2015) and most sons are likely to have lost their fathers,  
306 becoming *sui iuris* ('of one's own right'), and had themselves inherited the role – including  
307 the legal and financial independence - of the head of the household (*paterfamilias*). A  
308 second consideration is the high prevalence of slaves and freedmen in the city.  
309 Demographic estimates based on the Marble Album of Herculaneum suggest that a  
310 significant proportion of the town's urban population (ca. 23%) were freedmen (de Ligt and  
311 Garnsey, 2012). The study proposes that ca. 69% of the adult male citizen population were  
312 ex-slaves, and that ca. 60% of the entire urban slave population at Herculaneum were  
313 manumitted by the age of 30. With manumission came possible elevation to the rank of  
314 Roman citizen in accordance with the laws passed in the time of Augustus. Freedmen were  
315 normally involved *ipso facto* in a patronage relationship with their ex-masters, supposing the  
316 latter were still alive – in which case the freedman might benefit from a legacy (Aldrete,  
317 2008; Garnsey and Saller, 2015). In either eventuality, their standard of living and  
318 subsistence is likely to have improved following manumission, again permitting access to  
319 new foods. In comparison, female slaves were manumitted later in life, if at all. Furthermore  
320 if, as seems probable, freedmen were involved in the processing and trade of fish (Curtis,  
321 2005), they are also likely to have had preferential access to this resource, and be well-  
322 represented among those in the sample with high  $\delta^{15}\text{N}$  values.

323

324 A potential methodological explanation for the absence of strong isotopic differences by  
325 narrower age classes at Herculaneum is that the measurements are of collagen which is  
326 synthesised at different times within an individual's lifespan. As bone collagen turnover rate  
327 is relatively slow, a substantial proportion of collagen derived from earlier in life will still be  
328 present at death. For example, from studies of collagen turnover rates in femoral bone  
329 (Hedges *et al.*, 2007) we estimate that 63% of collagen in a 45 year old male, or 53% in a  
330 female of the same age, is derived from foods consumed before 30 years of age.  
331 Furthermore, the rate of bone turnover slows dramatically following adolescence, meaning  
332 that younger individuals' skeletons contain relatively more collagen synthesised from foods  
333 consumed closer to the time of death than older individuals. A slightly faster turnover rate  
334 may be anticipated in the rib samples analysed in this study, nevertheless, these  
335 measurements are unlikely to reflect true differences between the age classes. Indeed, the

336 differences that we observed are probably underestimations of the true dietary differences  
337 between the old and the younger adults at their time of death.  
338



339  
340  
341 **Fig 4: Boxplot of  $\delta^{15}\text{N}$  values at Herculaneum by age in years and sex.**  
342

343 Age related dietary differences were observed at Isola Sacra. Here, Prowse *et al.* (2005)  
344 showed that age and  $\delta^{15}\text{N}$  are positively correlated for both sexes. Explaining this  
345 observation is far from straightforward as it is not possible to distinguish whether individuals  
346 consumed a greater proportion of fish in later life or whether high fish consumers simply  
347 lived longer. Given the difficulties in interpreting isotopic data from bone collagen due to its  
348 slow turnover rate, and the lack of strong evidence of age related differences within the  
349 'living population' at Herculaneum, we suggest that the latter explanation is more likely. At  
350 Velia, there are no overall significant differences by age class (Craig *et al.*, 2009), however  
351 one group of adult males ( $n = 11$ ) are relatively enriched in  $^{15}\text{N}$  (i.e.  $> 9.6\text{‰}$ ) compared to the  
352 rest of the population. Interestingly, 10 are over 30 years of age and also have a much  
353 higher prevalence of external auricular exostosis (Crowe *et al.*, 2010), a pathology caused  
354 by regular exposure to cold water which is most likely linked to sea-related occupations  
355 (Crowe *et al.*, 2010).

#### 356 1.4. Conclusion

357 Overall, the data from the catastrophic assemblage at Herculaneum emphasizes the  
358 difficulty in interpreting intra-population isotopic variability in attritional cemetery populations,  
359 as are commonly encountered in archaeological research. There is less overall variation in  
360  $\delta^{15}\text{N}$  at Herculaneum compared to Velia and Isola Sacra regardless of sample size or  
361 demographic composition. This result is most easily explained by the short-lived nature of  
362 the population. Diets change over generations as the result of changes in the economy and  
363 food supply, as well as cultural shifts. Therefore, the range of foods eaten by individuals  
364 living contemporary lives may be considerably narrower than revealed through isotopic  
365 analysis of individuals buried in cemeteries, which are also influenced by selective mortality

366 and selective burial. This has important implications for considering the *durée* of cemetery  
367 populations before making comparisons of any osteological datasets. Despite these  
368 interpretative issues, underlying trends are still observable between osteological and isotopic  
369 datasets, for example due to occupation (Crowe *et al.*, 2010). However, we suggest that  
370 these correlations are probably related to an individual's long-term diet rather than directly  
371 attributable to specific periods of their life, given the attenuated dietary record represented  
372 by adult bone collagen. At the very least, such direct associations need to be questioned.  
373 Further comparison of stable isotope values of collagen from tissues with different turnover  
374 rates is needed to help resolve these issues. Finally, we confirm there is clear differentiation  
375 of diet by sex as observed in attritional Roman populations, related to differential access of  
376 males and females to marine foods.

377

378

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525 **Supporting information, Table 1. Carbon and nitrogen stable isotope values, and estimated % dietary contribution of marine-**  
 526 **derived carbon and nitrogen, of all sampled Herculaneum individuals. The 9 infant/juvenile individuals analysed here for the**  
**first time are marked with an asterix (\*). The remaining data are the same as presented in Craig *et al.*, (2013).**

Sample	Bone Element	Sex	Age at Death	%C	%N	Atom C:N	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	Carbon offset	Marine carbon (%)	Nitrogen offset	Marine nitrogen (%)
F7I7	Rib	M	20-30	41.7	15.2	3.2	-19.27	10.07	50.84	13.0	45.06	11.6
F7I9*	Rib	-	00-05	34.2	11.6	3.4	-19.28	11.37	50.20	12.9	89.93	23.1
F7I10	Rib	M	30-40	42.7	15.6	3.2	-18.75	10.63	80.13	20.5	64.41	16.5
F7I11*	Rib	-	00-05	37.8	13.4	3.3	-20.18	8.93	0.18	0.0	6.08	1.6
F8I6	Rib	F	20-30	35.6	12.6	3.3	-19.92	9.41	14.54	3.7	22.70	5.8
F8I7	Rib	M	40-50	42.4	15.5	3.2	-18.88	10.83	72.78	18.7	71.25	18.3
F8I8	Rib	F	40-50	45.2	16.7	3.2	-18.90	10.95	71.88	18.4	75.30	19.3
F8I10	Rib	-	10-15	42.2	15.5	3.2	-19.77	9.50	22.82	5.9	25.67	6.6
F8I11	Rib	-	15-20	43.4	16.0	3.2	-19.81	8.17	20.55	5.3	-19.85	-5.1
F8I13	Rib	F	30-40	40.6	14.9	3.2	-19.45	9.56	40.83	10.5	27.83	7.1
F8I15	Rib	-	15-20	31.1	10.5	3.5	-20.17	8.99	0.35	0.1	8.02	2.1
F8I17*	Rib	-	00-05	34.8	12.4	3.3	-19.28	10.21	50.20	12.9	50.05	12.8
F8I18	Rib	F	20-30	43.5	15.9	3.2	-19.40	9.61	43.66	11.2	29.42	7.5
F8I21	Rib	F	30-40	42.9	15.7	3.2	-19.67	9.26	28.77	7.4	17.54	4.5
F8I22	Rib	M	40-50	27.9	9.5	3.4	-19.22	10.29	53.93	13.8	52.71	13.5
F8I23	Rib	M	20-30	42.0	15.4	3.2	-19.57	9.10	34.21	8.8	12.08	3.1
F9I6*	Rib	-	05-10	44.2	15.3	3.4	-20.16	9.17	1.30	0.3	14.16	3.6
F9I9	Rib	M	40-50	43.4	15.6	3.3	-18.80	11.45	77.32	19.8	92.54	23.7
F9I13	Rib	M	40-50	42.6	15.3	3.2	-19.12	10.76	59.37	15.2	68.87	17.7
F9I27*	Rib	-	05-10	44.7	15.3	3.4	-19.99	10.11	10.56	2.7	46.40	11.9
F10I1	Rib	M	30-40	41.7	14.6	3.3	-18.21	9.05	110.39	28.3	10.12	2.6
F10I2	Rib	M	15-20	43.1	15.6	3.2	-19.02	10.18	64.92	16.6	48.96	12.6
F10I6	Rib	M	30-40	42.6	15.1	3.3	-18.79	11.07	78.04	20.0	79.40	20.4



F10I10	Rib	M	30-40	38.9	13.4	3.4	-19.30	11.72	49.31	12.6	101.65	26.1
F10I11	Rib	F	30-40	41.9	14.7	3.3	-19.70	9.31	26.83	6.9	19.13	4.9
F10I12	Rib	M	30-40	42.2	15.0	3.3	-19.01	10.64	65.34	16.8	64.71	16.6
F10I13	Rib	M	30-40	42.4	15.4	3.2	-19.18	11.67	55.79	14.3	100.05	25.7
F10I14	Rib	M	30-40	42.2	15.3	3.2	-19.02	10.54	64.72	16.6	61.22	15.7
F10I15	Rib	F	20-30	42.9	15.7	3.2	-18.96	10.63	68.44	17.5	64.28	16.5
F10I16	Rib	F	30-40	43.7	15.3	3.3	-19.79	10.09	21.78	5.6	45.89	11.8
F10I17	Rib	M	30-40	41.4	15.2	3.2	-18.84	11.57	74.98	19.2	96.76	24.8
F10I18	Rib	F	30-40	44.0	16.1	3.2	-19.27	9.94	50.89	13.0	40.74	10.4
F10I19	Rib	M	30-40	42.0	15.3	3.2	-19.04	10.55	63.63	16.3	61.58	15.8
F10I20	Rib	M	40-50	43.1	15.6	3.2	-19.59	9.14	32.86	8.4	13.21	3.4
F10I22	Tarsal bone	M	20-30	43.1	15.8	3.2	-19.07	10.49	62.00	15.9	59.52	15.3
F10I23	Rib	M	30-40	42.2	15.2	3.2	-19.07	9.10	61.91	15.9	11.92	3.1
F10I24	Rib	F	40-50	40.2	14.4	3.3	-18.96	10.09	68.36	17.5	45.84	11.8
F10I25	Long bone	M	20-30	41.3	15.1	3.2	-18.98	9.51	67.36	17.3	26.12	6.7
F10I28	Rib	F	30-40	41.6	15.0	3.2	-19.65	9.16	29.64	7.6	13.99	3.6
F10I29	Rib	F	20-30	42.8	15.6	3.2	-19.32	10.49	48.16	12.3	59.46	15.2
F10I35	Tarsal bone	M	20-30	41.7	15.2	3.2	-19.12	9.87	59.60	15.3	38.47	9.9
F10IA	Rib	F	50+	40.9	15.3	3.1	-20.12	9.01	3.38	0.9	8.76	2.2
F10IB	Rib	-	-	40.9	15.1	3.2	-19.31	10.00	48.51	12.4	42.65	10.9
F11I1*	Rib	-	00-05	34.8	13.0	3.1	-19.09	9.68	60.99	15.6	31.69	8.1
F11I2*	Rib	-	10-15	40.8	15.2	3.1	-19.23	9.00	53.48	13.7	8.53	2.2
F11I3*	Rib	-	10-15	38.6	14.1	3.2	-19.53	8.80	36.62	9.4	1.47	0.4
F11I4	Rib	F	15-20	36.8	14.0	3.1	-19.10	10.25	60.71	15.6	51.20	13.1
F11I5	Long bone	M	15-20	35.8	13.3	3.2	-18.62	11.03	87.36	22.4	78.20	20.1
F11I6	Rib	F	40-50	32.7	12.4	3.1	-19.12	10.29	59.56	15.3	52.85	13.6
F11I7	Rib	F	40-50	42.6	16.2	3.1	-19.19	9.67	55.72	14.3	31.53	8.1
F11I8	Long bone	F	20-30	39.2	15.0	3.0	-18.76	10.70	79.68	20.4	66.81	17.1
F11I9	Rib	M	20-30	43.2	16.7	3.0	-18.71	9.30	82.45	21.1	18.65	4.8
F11I10	Rib	M	15-20	38.8	15.0	3.0	-19.11	9.13	59.90	15.4	13.06	3.3
F11I11*	Rib	-	10-15	39.2	14.9	3.1	-19.14	9.48	58.41	15.0	24.88	6.4

F11I14	Rib	M	30-40	41.1	15.8	3.0	-19.07	10.34	62.17	15.9	54.38	13.9
F11I15	Rib	F	15-20	39.8	15.0	3.1	-19.38	9.33	44.87	11.5	19.68	5.0
F11I16	Rib	M	Adult	36.0	13.2	3.2	-19.49	10.23	38.70	9.9	50.57	13.0
F11I18	Rib	M	40-50	40.3	15.2	3.1	-19.23	10.00	52.97	13.6	42.75	11.0
F11I19	Rib	-	15-20	39.6	15.1	3.1	-19.38	9.46	44.61	11.4	24.14	6.2
F11I20	Rib	F	20-30	39.7	15.1	3.1	-18.83	10.09	75.64	19.4	46.02	11.8
F11I21	Rib	F	30-40	36.8	13.9	3.1	-19.21	10.43	54.21	13.9	57.38	14.7
F11I22	Rib	-	15-20	34.2	11.6	3.4	-20.00	9.15	9.83	2.5	13.71	3.5
F11I23	Rib	-	-	38.6	13.9	3.2	-19.33	9.58	47.67	12.2	28.22	7.2
F12I2	Rib	F	20-30	41.3	14.9	3.2	-19.30	10.51	49.55	12.7	60.17	15.4
F12I3	Rib	F	20-30	43.8	15.5	3.3	-19.67	10.09	28.51	7.3	45.89	11.8
F12I4	Rib	M	20-30	41.9	15.1	3.2	-19.25	10.27	52.22	13.4	52.03	13.3
F12I5	Rib	M	15-20	43.5	15.7	3.2	-19.55	9.89	35.03	9.0	39.09	10.0
F12I7	Rib	M	15-20	43.1	15.5	3.2	-19.21	10.54	54.21	13.9	61.36	15.7
F12I8	Rib	M	30-40	43.8	15.8	3.2	-19.05	10.50	63.14	16.2	59.96	15.4
F12I9	Rib	F	20-30	41.4	15.1	3.2	-19.47	10.02	39.50	10.1	43.54	11.2
F12I11	Rib	M	50+	42.0	15.4	3.2	-19.33	10.48	47.72	12.2	59.22	15.2
F12I13	Rib	F	30-40	43.7	15.9	3.2	-19.18	10.09	55.99	14.4	46.06	11.8
F12I15	Rib	F	30-40	41.9	15.4	3.2	-18.76	11.43	79.47	20.4	91.92	23.6
F12I16	Rib	M	30-40	42.2	15.3	3.2	-19.40	10.72	43.75	11.2	67.61	17.3
F12I19	Rib	M	30-40	37.9	13.5	3.3	-19.42	10.74	42.64	10.9	68.35	17.5
F12I23	Rib	M	40-50	43.7	15.5	3.3	-18.57	10.93	90.22	23.1	74.70	19.2
F12I26	Rib	M	30-40	39.8	14.4	3.2	-19.20	11.11	55.13	14.1	80.79	20.7
F12I27	Rib	M	30-40	41.5	14.8	3.3	-19.58	9.35	33.46	8.6	20.66	5.3
F12I28	Rib	F	30-40	42.4	15.2	3.2	-19.89	8.89	16.17	4.1	4.73	1.2
F12I30	Long bone	F	30-40	42.6	15.5	3.2	-19.09	9.08	60.89	15.6	11.21	2.9
F12I31	Phalanx	F	30-40	40.6	14.8	3.2	-19.07	10.71	62.24	16.0	67.24	17.2