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Statistically robust representation and comparison of mortality profiles in archaeozoology

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1 TITLE:

2 Statistically Robust Representation and Comparison of Mortality Profiles in
3 Archaeozoology

4

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20 ABSTRACT:

21 Archaeozoological mortality profiles have been used to infer site-specific
22 subsistence strategies. There is however no common agreement on the best way
23 to present these profiles and confidence intervals around age class proportions.
24 In order to deal with these issues, we propose the use of the Dirichlet
25 distribution and present a new approach to perform age-at-death multivariate
26 graphical comparisons. We demonstrate the efficiency of this approach using
27 domestic sheep/goat dental remains from 10 Cardial sites (Early Neolithic)
28 located in South France and the Iberian Peninsula. We show that the Dirichlet
29 distribution in age-at-death analysis can be used: (i) to generate Bayesian
30 credible intervals around each age class of a mortality profile, even when not all

31 age classes are observed; and (ii) to create 95% kernel density contours around
32 each age-at-death frequency distribution when multiple sites are compared
33 using correspondence analysis. The statistical procedure we present is
34 applicable to the analysis of any categorical count data and particularly well-
35 suited to archaeological data (e.g. potsherds, arrow heads) where sample sizes
36 are typically small.

37

38 KEY WORDS: archaeozoology, mortality profiles, sheep/goat, dental wear,
39 Dirichlet distribution, Cardial Neolithic

40

41 1. INTRODUCTION:

42 There is a high correlation between the known-age of an animal and its stage of
43 tooth eruption and wear (e.g. for domesticate animals Ducos 1968; Payne 1973;
44 Zeder 2006). Dental eruption and development have been employed to estimate
45 age-at-death distributions for animals for several centuries (Cornevin and Lesbre
46 1894). Archaeozoologists typically use the eruption through the mandible or
47 maxilla bone, development and replacement of teeth, which can be arranged into
48 fixed age classes (e.g. Payne 1973; Klein and Cruz-Urbe 1984; Stiner 1990;
49 Helmer 1995; Lubinski 2000; Zeder 2006). Although the recovery of dental
50 remains is influenced by depositional practices of cranial material in the past
51 (and may be biased towards certain age groups, and possibly sexes) and
52 excavation protocols, teeth often have a greater survival rate compared to
53 cranial and post-cranial elements (Lyman 1994a). In addition, the accuracy of
54 caprine (Caprini Simpson 1945) age determination using teeth has been
55 assessed (Hambleton 1999; Jones 2005; Greenfield and Arnold 2008) and
56 reproduced (Helmer 1995; Vila 1998). Teeth eruption and wear patterns are
57 generally regarded as the best proxy for age-at-death, and for inferring slaughter
58 management practices (Vigne and Helmer 2007).

59 The frequency distribution of age-at-death classes inferred from dental remains
60 – either as minimum number of individuals (MNI) or number of teeth (N) (Vigne
61 1988) – can be visualised using (i) ternary diagrams (Greenfield 1988; Stiner

62 1990; Steele and Weaver 2002; Steele 2005; Weaver, Boyko, and Steele 2011),
63 (ii) survivorship curves (Payne 1973), (iii) frequency polygons (Ducos 1968;
64 Vigne 1988; Vigne 2000) and (iv) histograms; also called mortality profiles
65 (Brochier 2013). Interpretation of survival profiles is necessarily made assuming
66 that all animals at an archaeological site have been killed by humans and that no
67 animals or age classes have been preferentially removed from the site. Testing
68 these assumptions can be very challenging. This is why in this study we favour
69 mortality profiles, which are direct representations of what is observed in an
70 archaeological site/context. We also favour histograms as an intuitive means of
71 visualizing frequency distributions; such graphical representation has become
72 very popular in the last few decades among archaeozoologists (Tresset 1997;
73 Tresset and Vigne 2000; Steele 2005; Helmer, Gourichon, and Vila 2007; Vigne
74 and Helmer 2007; Atıcı 2009; Makarewicz 2009).

75 The frequency distribution of domesticated animals within age classes varies
76 depending on the slaughter management and the goals of the husbandry strategy
77 (Higham 1967; Payne 1973; Helmer et al. 2005; Vigne and Helmer 2007), as well
78 as on sampling variation (Millard 2006). Consequently, if we assume that the
79 teeth or individuals determined from dental remains can be used as a proxy for
80 past slaughter management, assessing how this frequency distribution changes
81 through time can help to understand the evolution of husbandry practices
82 (Ducos 1968; Payne 1973; Vigne 1988; Helmer 1992; Halstead 1998; Helmer et
83 al. 2005).

84 However, various factors can affect the recovery of dental remains. The non-
85 observation within a given age class may be due to specific herd management
86 practices, or to under-sampling, or to taphonomic biases that are independent of
87 the management practices (Halstead 1998; Munson 2000). In addition, the
88 different durations of the age class categories may bias the frequency of dental
89 remains recorded. The number of teeth in the mandible varies with age, which
90 should favour the frequency of the age classes in which the number of teeth is
91 the higher (Masset 1973).

92 These biases have two opposing effects on interpretation and comparison of age-
93 at-death profiles: (i) a lack of confidence in relative frequencies due to the likely

94 misrepresentation of certain age classes (Greenfield 2005) and (ii) over-
95 interpretation of mortality profiles comparisons (Halstead 1998; Marom and
96 Bar-Oz 2009). While a robust Bayesian approach to aging individual sheep/goats
97 from toothwear exists (Millard 2006), there is no appropriate statistical means
98 of accounting for sampling uncertainty around a single, or over comparisons of
99 multiple, observed age-at-death frequency distribution(s).

100 More specifically, statistical challenges remain in the way different profiles are
101 compared among sites. While rank comparisons (Helmer 1992), confidence
102 intervals (Tresset 1997; Valenzuela-Lamas et al. 2009), or statistical tests (Chi²:
103 (Klein and Cruz-Urbe 1984; Haber, Dayan, and Getzo 2005); Spearman r test:
104 (Vigne 2000); Kolmogorov-Smirnov: (Marom and Bar-Oz 2009); Fisher exact
105 test: (Brochier 2013)); bootstrapping: (Steele 2005; Price, Wolfhagen, and
106 Otárola-Castillo 2016) have been applied, none of these techniques adequately
107 assesses the high level of sampling uncertainty in age-at-death data (see
108 discussion). For example, a Chi² test requires the data to meet the following
109 assumptions: (i) independence of each observation, (ii) no outliers, (iii) no
110 structural zeroes (Yates, Moore, and McCabe 1999). These assumptions are
111 however not met in the case of age-at-death data since (i) age classes are not
112 independent, (ii) archaeological data is by nature scarce, and outliers are not
113 rare in this context, and (iii) zeroes may exist for some age classes.

114 Several scholars have proposed the use of multivariate correspondence analysis
115 to visualise and compare a set of age-at-death profiles, rather than testing them
116 with reference to statistical thresholds (Tresset 1996; Vigne 2000; Helmer,
117 Gourichon, and Vila 2007; Vigne 2011; Gillis 2012). However, while well suited
118 for visualizing the similarities and differences between profiles, correspondence
119 analysis does not in itself provide any means of assessing statistical confidence of
120 groupings or clusters, or of quantifying differences between observed profiles.

121 To account for sampling uncertainties in the downstream analysis and
122 interpretation of age-at-death profiles, we propose the use of the Dirichlet
123 distribution to generate random deviates of the population age-at-death profile
124 given an observed sample or samples. The Dirichlet distribution is the conjugate
125 prior of the multinomial distribution and can be used in a Bayesian framework to

126 provide probability densities for the relative frequencies of age classes given
127 observed counts in those classes and an appropriate prior. This distribution has
128 been widely used as a model of how proportions vary (e.g. Rannala and
129 Mountain 1997; Wong 1998; Chikhi, Bruford, and Beaumont 2001; Balding 2003;
130 Madsen, Kauchak, and Elkan 2005), where the sum of these proportions equals 1,
131 as is the case for age-at-death profiles (Millard 2006).

132 In this study, we first show how the Dirichlet distribution can be used to
133 generate credible intervals around the age classes of an observed mortality
134 profile. We then illustrate how this can be used to estimate confidence intervals
135 on correspondence analysis plots comparing age-at-death frequency
136 distributions from multiple sites. Here we apply this method to age-at-death data
137 based on tooth eruption, replacement and wear patterns. However, we note that
138 it can be used to analyse any categorical count data (e.g. potsherds, arrow
139 heads).

140

141 2. DATASET and METHODOLOGY:

142 2.1. Dataset

143 In order to illustrate the robustness of our approach and to assess its sensitivity
144 to clustering of sites with relatively homogeneous cultural backgrounds, we
145 considered ten sites (Table 1 and Figure 1) from France and the Iberian
146 Peninsula belonging to the Cardial, Epicardial or assimilated cultures of the
147 North-West Mediterranean Early Neolithic and dated between 5500 and 4500
148 cal BC. These data are a part of a larger dataset collated for a PhD project (Gillis
149 2012); data for all sites were recovered from published sources (Boessneck and
150 Von den Driesch 1980; Vigne 1988; Helmer, Gourichon, and Vila 2007), except
151 for Font Juvenal and La Draga (see Table 1). We followed Payne (1973) and
152 Ducos (1968) methodologies of study for all sites, except for Cueva de Sarsa, for
153 which we used Habermehl (1975).

154

155 Table 1: Ten early Neolithic sites from southern France and the Iberian Peninsula
 156 were used in the present analysis (age classes following (Payne 1973; Helmer
 157 1995); the data is the number of teeth in each age class (N_i) and come from (*)
 158 Gillis (2012), (#) Helmer et al. (2007) , (\$) Boessneck and Von den Driesch
 159 (1980) and (§) Vigne (1988). Non-integer N_i values reflect that a tooth can be
 160 classified in to more than one age class and the number of teeth is therefore
 161 divided into as many age classes as it could be assigned to. The site locations are
 162 shown on Figure 1. Additional chronological information and references can be
 163 found in Vigne (2007) and Rowley-Conwy et al. (2013, Tab. 9.4 & 9.5).

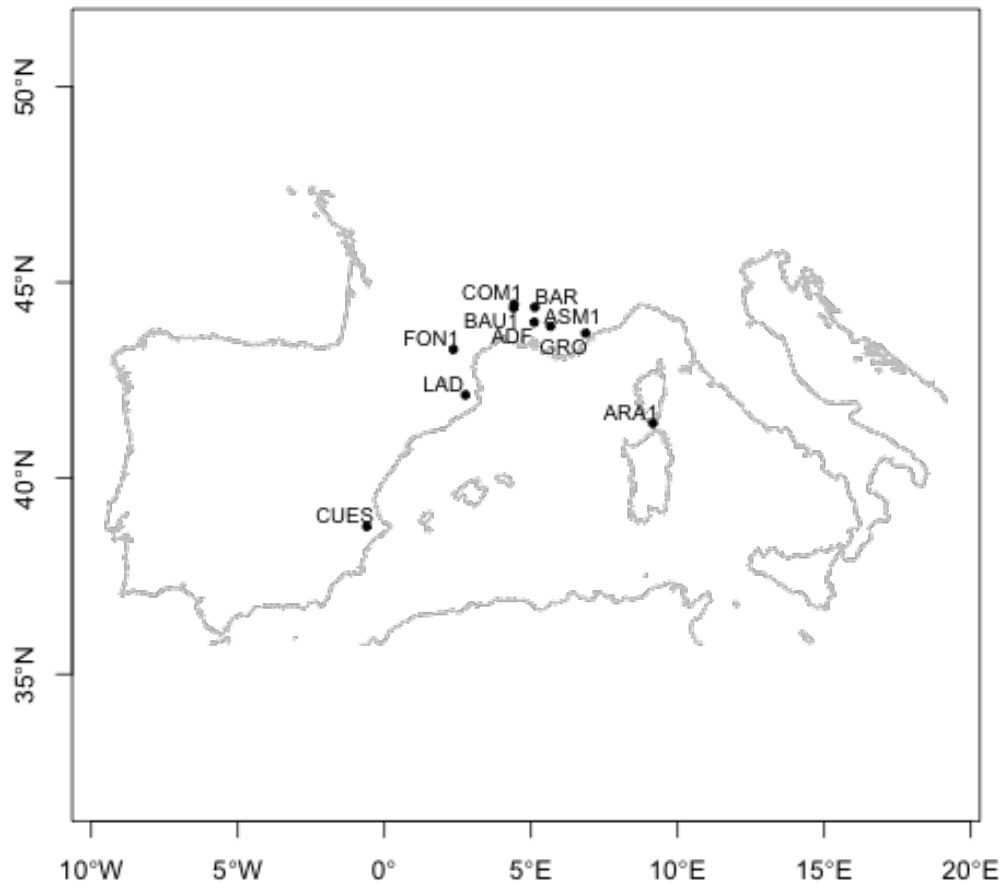
Site (reference)	Code	Age classes								Total N	Site type
		A	B	C	D	EF	G	HI			
La Draga (*)	LAD	0	5.7	15.7	56.1	48.6	18.6	0	145	open	
Grotte Lombard (#)	GRO	1	3	3	4	9	7	1	28	cave/rockshelter	
Font Juvenal I (*)	FON1	7.5	2.66	9.66	12.16	5.66	4.66	1.66	44	cave/rockshelter	
Cueva de la Sarsa (§)	CUES	1	9	9	6	13	2	1	41	cave/rockshelter	
Combe Obscure I (#)	COM1	2	5	10	4	4	3	7	35	cave/rockshelter	
Baume d'Oulen I (#)	BAU1	6	6	9.5	7.5	5.75	2.25	1	38	cave/rockshelter	
Barret de Lioure (#)	BAR	0	2	9	4	8	5	1	29	cave/rockshelter	
Abri de Saint-Mitre I (#)	ASM1	0	1	6	2	2	3	0	14	cave/rockshelter	
Araguina-Sennola I (§)	ARA1	3	6.5	6.5	14	7	0	0	37	cave/rockshelter	
Abri II du Fraischamp (#)	ADF	0	3	5	6	5	2	0	21	cave/rockshelter	

164

165

166 Figure 1: Geographic locations of the 10 Early Neolithic sites analysed here. The
167 site codes are given in Table 1.

168



169

170

171

172 2.2. Graphical and statistical methodology

173 All statistical analysis and generation of graphical representations were
174 performed using the statistical analysis scripting language R, version 2.15.1 (R
175 Development Core Team 2012). Plots were generated using the R library
176 “ggplot2” (Wickham 2009). The R code developed and example input files are
177 available at < <http://www.ucl.ac.uk/mace-lab/resources/software>>.

178 2.3. Histograms

179 We displayed age-at-death frequency distributions amongst the seven age
180 classes using histograms where the unit of the x-axis is in years. Since distinct
181 age classes have different time lengths (Table 2, age class width W_i column), and
182 to respect the continuous x-axis unit, the 7 bin widths are unequal. This is one of
183 the major differences to the recently published R package “zooaRch” (Price,
184 Wolfhagen, and Otárola-Castillo 2016), where the age classes have equal bin
185 width on the x-axis. In “zooaRch” the relationship between area under the curve
186 and mean survival age (e.g. Fries 1980) is lost (Price, Wolfhagen, and Otárola-
187 Castillo 2016), while it is conserved in the current approach. The frequency
188 density in counts per unit of time (histogram y-axis, example on Table 2) is
189 obtained by dividing the frequency by the bin width W_i . The y-axis of the
190 histograms is consequently in units of corrected number of teeth observed in a
191 given age class, i.e. N_i/W_i (see column “Corrected N_i ” in Table 2). Please note that
192 the scope of this study was to address statistical challenges faced by existing
193 mortality profile techniques, i.e. histogram representation with x-axis unit in
194 years. Since alternative representations would also involve debates concerning
195 the counting protocol, we did not explore alternatives, such as representation
196 accounting for the different number of cheek teeth per age class ((Masset 1973);
197 Table 2, last column), but this aspect of the analysis of age-at-death data should
198 be investigated in the future.

199

200 Table 2: Description of the 7 age classes used for sheep and goat (Payne 1973;
201 Helmer et al. 2005), and data from the archaeological site of Font Juvenal I (Gillis
202 2012). The age class width vector W_i is obtained by dividing the estimated age in

203 months by 12 for drawing the continuous x-axis scale unit of the histogram (in
 204 years). The frequency density on the y-axis of the mortality profile (Figure 1 and
 205 S1) is the time-corrected N_i , i.e. (N_i/W_i) . The last column shows the maximum
 206 number of cheek teeth (except the second premolar) that are actually present in
 207 a half lower jaw of a sheep/goat during this age class, including the tooth buds.

Age class i	Estimated age (months)	Age class width W_i (years)	Number of teeth N_i	Frequency density (N_i/W_i)	Maximum no. of cheek teeth in a lower hemimandible (except the second premolar)
A	0-2	0.17	7.50	44.12	2
B	2-6	0.33	2.66	8.06	3
C	6-12	0.5	9.66	19.32	4
D	12-24	1	12.16	12.16	7
EF	24-48	2	5.66	2.83	6
G	48-72	2	4.66	1.17	5
HI	72+ (up to 120)	4	1.66	0.42	5

208

209

210 2.4. Dirichlet distribution and Bayesian credible intervals

211 Relative frequencies (p_i) of an age-at-death count distribution can be obtained
 212 from the absolute frequencies (N_i), where i represent the age classes (i.e. age
 213 classes A, B, C, D, EF, G and HI). As $\sum p_i = 1$, the individual p_i values are not
 214 independent, and estimating confidence intervals can be challenging. However,
 215 credible intervals can be computed from the probability density function of the
 216 Dirichlet distribution, with 7 parameters $\text{Dir}(N_A+0.5, N_B+0.5, N_C+0.5, N_D+0.5,$
 217 $N_{EF}+0.5, N_G+0.5, N_{HI}+0.5)$ to obtain the true population frequency distribution of
 218 age-at-death. The addition of 0.5 to each count for each age class corresponds to
 219 the uninformative Jeffreys' prior (Jeffreys 1946; Jeffreys 1961). Because we
 220 perform downstream analyses on these population age-at-death frequency
 221 estimates (see section 2.5, below), we first generated 10,000 Dirichlet deviates of
 222 the population age-at-death frequency distribution.

223 An “uninformative prior” is a function that maximizes some measure of distance
 224 or divergence between the posterior and prior, as data observations are made.
 225 By maximizing the divergence, we allow the data to have the maximum effect on
 226 the posterior estimates. The Jeffreys' prior satisfies the local uniformity

227 property: a prior that does not change much over the region in which the
228 likelihood of the data is significant and does not assume large values outside that
229 range. We note that for other archaeological dataset a different prior may be
230 more appropriate.

231 Random deviates of the population age-at-death frequency distribution were
232 generated using the 'rdirichlet' function (Bolker 2000) from the R library
233 "gtools" (CRAN repository, <http://cran.r-project.org/web/packages/gtools/>).
234 The 'rdirichlet' function considers absolute counts from the sample and returns
235 random deviates of the population relative frequencies, given the observed data.
236 We subsequently multiply each Dirichlet deviate by the number of teeth
237 observed at the corresponding archaeological site in order to obtain comparable
238 simulated datasets. The Dirichlet deviates were then divided by the bin width
239 (W_i) to obtain the corresponding frequency density distribution per unit time.
240 These Dirichlet deviates were finally used to obtain the 95% credible interval of
241 each age class using the 'p.interval' function (Bernardo 2005) from the R package
242 "LaplacesDemon" (Byron Hall <laplacesdemon@statistcat.com> 2012) and
243 plotted on the histograms.

244 2.5. Correspondence Analysis and kernel density estimation

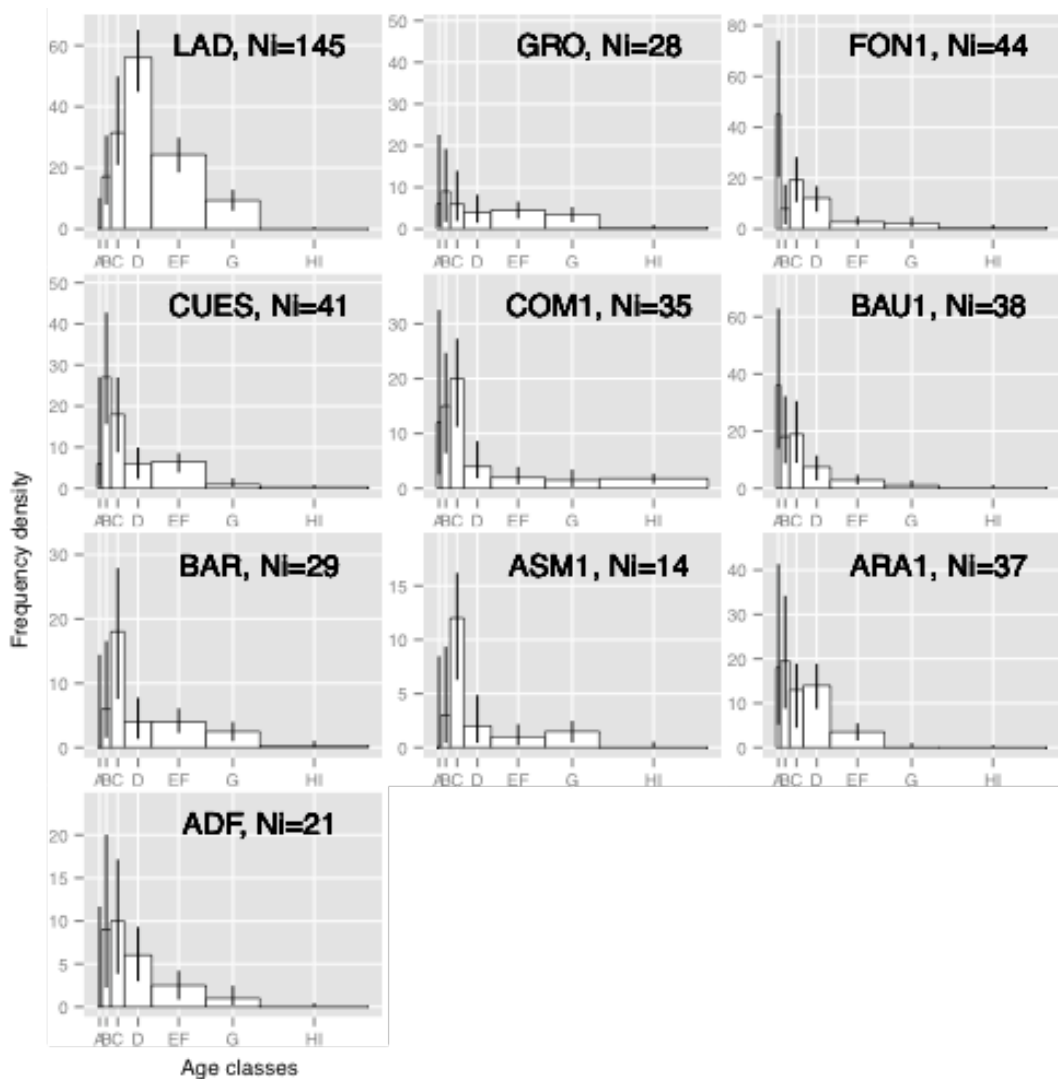
245 Correspondence analysis is a useful multivariate descriptive statistical technique
246 for summarizing multiple rows and columns of categorical data in two or more
247 dimensions (Benzécri 1973). Correspondence analysis was performed on an
248 array made of the 10 observed age-at-death profiles and each of their 10,000
249 Dirichlet random deviates using the 'ca' function (Nenadic and Greenacre 2007)
250 from the R library "ca" (CRAN repository, [http://cran.r-](http://cran.r-project.org/web/packages/ca/)
251 [project.org/web/packages/ca/](http://cran.r-project.org/web/packages/ca/)). Kernel density estimation is a non-parametric
252 approach to estimate the probability density of a random variable, (Parzen
253 1962). We used these 10,000 Dirichlet deviates to estimate the two-dimensional
254 kernel density for each mortality profile. The density was estimated using the
255 'kde2d' function (Venables and Ripley 2002) from the R library "MASS" (CRAN
256 repository, <http://cran.r-project.org/web/packages/MASS/>). We then obtained
257 the fifth quantile density value, above which 95% of the values lie. This was
258 performed using the R function 'quantile'. We then plotted the contour lines

259 around this fifth quantile, showing the region in which 95% of the deviates fall,
260 thereby representing the 95% confidence interval of each mortality profile on
261 the correspondence analysis plot. The 95% confidence intervals were drawn
262 using the R function 'contour' (Becker, Chambers, and Wilks 1988).

263 It should be noted that we compute credible intervals on the age-at-death
264 profiles (i.e. the histograms) but confidence intervals on the correspondence
265 analysis. The former are directly obtained from the Dirichlet deviates of the
266 observed age-at-death data, used as a posterior probability distribution, and are
267 consequently by definition credible region estimates. However, in the
268 correspondence analysis, we used these Dirichlet deviates to define a range of
269 values so that there is a specified probability (95%) that the value for the site lies
270 within it. Hence we refer to these as confidence intervals and not credible
271 intervals.

272

273 Figure 2: Mortality profile representations of the 10 observed age at death
 274 frequency distributions (observed number of teeth per age class) shown in Table
 275 1. The x-axis (age classes) is on a continuous scale in years. The y-axis is the
 276 frequency per unit time density, where frequency per unit time density =
 277 frequency / bin width (N_i/W_i ; see Table 2). The black vertical bars represent the
 278 95% credible intervals of the frequency density through time computed from the
 279 10,000 Dirichlet deviates generated on the ($N_i+0.5$) observed age at death
 280 frequency distribution (see above for further details).



281

282

283 3. RESULTS:

284 The properties of the Dirichlet distribution permit the generation of random
285 deviates of the population frequencies given the observed sample data and a
286 suitable prior. Figure 2 represents the 10 mortality profiles presented in Table 1,
287 with 95% credible intervals of the frequency density through time, generated by
288 10,000 Dirichlet deviates.

289 All 7 age classes are represented on the age-at-death data from the
290 archaeological site Font Juvenal I (FON1, Table 1 and Table 2, number of teeth N_i
291 > 0). The youngest age class (A) has the largest credible interval, while the oldest
292 age class (HI) has the smallest, which is directly related to their observed counts
293 (Figure 2). There is no overlap between the credible intervals of class A and any
294 of the other classes, except class C. This increases our ability to differentiate
295 between age class representations in an archaeological sample. It should be
296 noted that these are 95% credible intervals on the frequency density per unit
297 time of each age class, and not on the frequency in each age class.

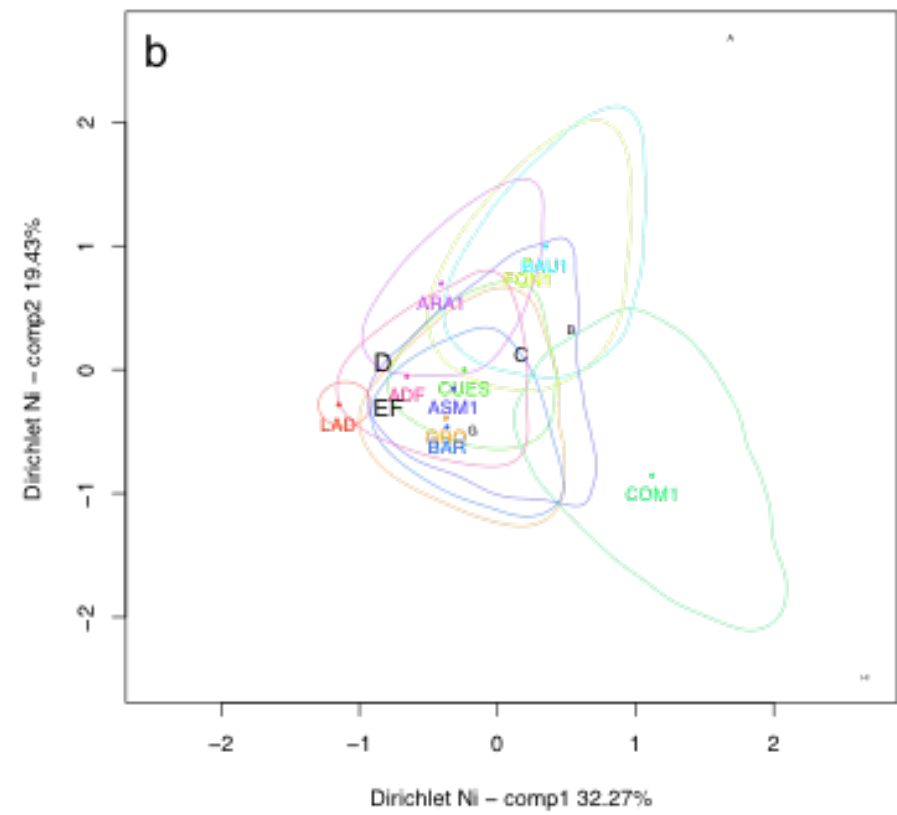
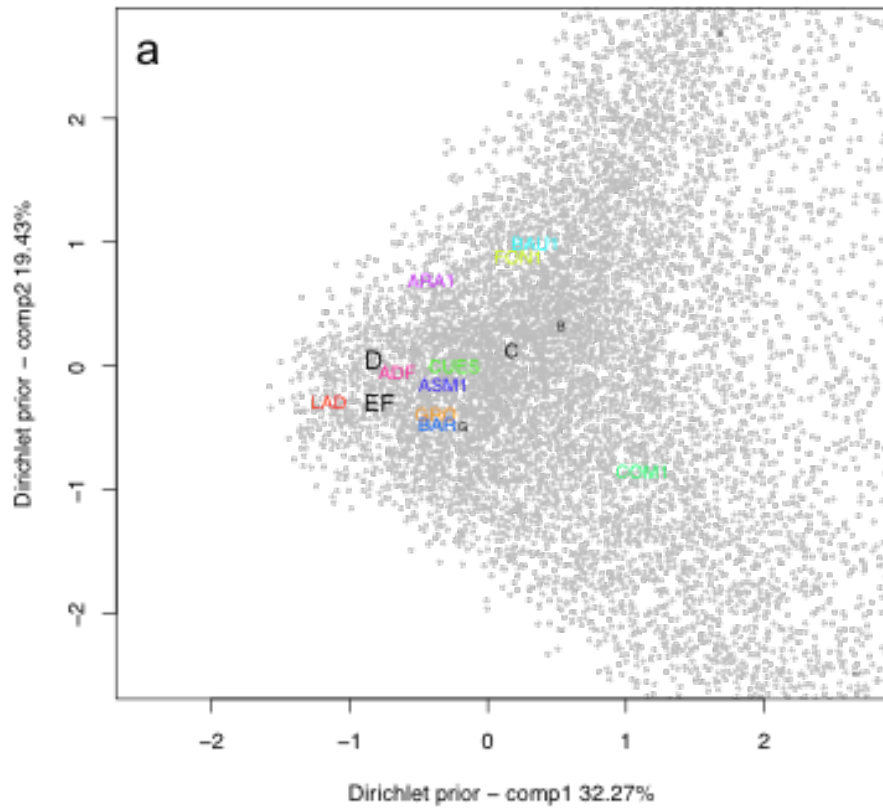
298 Similarly, on the age-at-death frequency distribution of the archaeological site La
299 Draga (LAD), there is no overlap between the credible intervals of class D and
300 any of the other age classes, except with class C (Figure 2). Here again, our
301 approach enables us to be more confident when interpreting the observed
302 pattern. More specifically, while the youngest and the oldest age classes are not
303 observed on this profile (Table 2, number of teeth $N_i = 0$), the properties of the
304 Dirichlet distribution allow us to generate random deviates of the population
305 age-at-death frequency distribution and estimate credible intervals for those
306 unrepresented classes.

307 The credible intervals of the youngest age class (A) are generally the widest
308 (Figure 2). The Cueva de Sarsa – CUES profile contrasts well against those from
309 Font Juvenal – FON1 and La Draga – LAD. There is less visible contrast between
310 the profiles from Combe Obscure 1 – COM1, Baume d'Oulen – BAU1, and Abri I de
311 Saint Mître – ASM1. For Barret de Lioure – BAR, Abri II du Fraischamp – ADF,
312 Araguina-Sennola – ARA1 and Grotte Lombard – GRO in general, nearly all the
313 credible intervals overlap, suggesting low differentiation or poor resolution in
314 the data.

315

316 Figure 3: Correspondence analysis performed on the ten Cardial, Epicardial and
317 assimilated archaeological culture mortality profiles from France and the Iberian
318 Peninsula, dated to between 5500 and 4500 cal BC (Table 2). The site and age
319 class coordinates are those for the first two dimensions of the correspondence
320 analysis (representations on dimensions 1 and 3 and 2 and 3 are shown on
321 Figure S1a and S1b, respectively). The site codes (coloured names) are given in
322 Table 1. The relative positions of the age classes are shown in black and their
323 font size is proportional to their relative contribution to the analysis (Table S2).
324 Age classes A (at the top right corner) and HI (at the bottom right corner) are in
325 small font size because of their small contribution to the representation. Figure
326 3a (left): Grey dots are some of the 10,000 deviates of the population frequency
327 given the observed data, using the Jeffreys' prior, i.e. 'rdirichlet (0.5, 0.5, 0.5, 0.5,
328 0.5, 0.5, 0.5)'. Figure 3b (right): Correspondence analysis and kernel density
329 estimates of the 10 mortality distributions. The two-dimensional kernel density
330 estimates for an age-at-death frequency distribution (i.e. one site) were obtained
331 from the x and y coordinates generated by the correspondence analysis for the
332 10,000 Dirichlet deviates of this site. The contour lines were drawn around the
333 density value containing 95% of the deviates. Colour dots show the relative
334 position of the observed age-at-death frequency distribution for the
335 corresponding sites.

336



337

338

339
340 Correspondence analysis was performed on the observed number of teeth (N_i)
341 per age class i to compare the ten age profiles (see Table S1 for the proportion of
342 variations explained by the Correspondence Analysis components). Figure 3a
343 and 3b represent the projections of the first two components, i.e. summarizing
344 52% of the total variation. Figure 3a shows that the age classes (black letters) are
345 arranged according to the age gradient (A to HI class; the “Guttman effect”). The
346 distribution of the age classes and sites (coloured names) for the observed data
347 only, in two dimensions, overlaid with the 10,000 random deviates (grey dots)
348 obtained from Jeffreys’ prior, i.e. ‘`rdirichlet(0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5)`’. The
349 cloud of grey dots represents the correspondence analysis distribution of
350 Dirichlet simulated mortality profile. It can be thought of as the Correspondence
351 Analysis projection of a null distribution of age-at-death data, i.e. expected
352 correspondence analysis plot, given only the prior. As expected, this cloud of
353 random points covers the range of the 10 observed mortality profiles. This
354 highlights that any interpretation of correspondence analysis plots, without
355 statistical assessment, can be misled by the shape of the possible plot space,
356 which is itself determined by the input data. Such factors should be considered
357 when comparing age-at-death frequency distributions using such plots. Figure
358 3b shows the contour lines representing the confidence interval for an observed
359 age-at-death frequency distribution within which 95% of the deviates lay.

360 The use of the kernel density estimation aids interpretation of
361 similarity/dissimilarity of age-at-death profiles to the extent that it provides
362 areas of possible overlap with statistical confidence. Figure 3b indicates that we
363 can be confident at approximately the 0.05% level that two clusters of sites
364 overlap: the first contains five sites (GRO, CUES, BAR, ASM1, ADF) and the second
365 contains (BAU1 and FON1). The overlap of these sites within each cluster
366 suggests that their slaughter profiles cannot be differentiated, and could be
367 interpreted as indicating similar slaughtering strategy within each cluster, or
368 poor resolution in the data. Figure 3b also indicates that three sites do not
369 overlap with one another (LAD, ARA1, COM1). This suggests that these sites’
370 mortality profiles differ significantly, which may represent specific slaughter

371 strategies, differences in taphonomic loss or management of the carcasses
372 occurring at these sites.

373 It should be noted that the correspondence analysis reported in this study
374 necessarily only shows 2 dimensions of variation; further dimensions of
375 variation may permit statistical differentiation of observed datasets. We
376 recommend exploration of dimensions of variation beyond the first 2 before
377 confidently stating that 2 datasets are not statistically differentiated (see, for
378 example, Figures S1a and S1b).

379

380 4. DISCUSSION:

381 This study demonstrates how the Dirichlet distribution can be used to produce
382 credible intervals for mortality profiles and confidence intervals on
383 correspondence analysis, even when some age classes are not observed, as an aid
384 to interpretation of clustering patterns. Below we discuss interpretation of age-
385 at-death frequency distributions and comparisons of these distributions using
386 correspondence analyses.

387 4.1. Methodological considerations

388 The accumulation of age-at-death data over the last few decades, and its use to
389 make inferences on animal domestication and husbandry strategies, has
390 highlighted a number of theoretical and methodological challenges (Brochier
391 2013). Some of these challenges are due to (i) the high sampling uncertainty
392 associated with archaeological assemblages (ii) the discretization of age
393 estimates into non-independent age categories. The latter generates
394 categorization uncertainty that depends on the number and duration of the age
395 classes, as well as on precision with which teeth can be attributed to one age
396 class or another (Steele 2005).

397 Even though some archaeozoological studies have attempted to deal with these
398 issues (Price, Wolfhagen, and Otárola-Castillo 2016), we believe the statistically
399 tractable approach we propose here has 4 major advantages over other existing
400 approaches. First, it infers the joint distribution of the population frequencies of
401 the 7 age classes and provides a better resolution of the underlying herding

402 strategy than ternary diagrams, which use only 3 age classes (Steele 2005;
403 Weaver, Boyko, and Steele 2011). Second, analogous to Millard (Millard 2006)'s
404 Bayesian approach, sampling uncertainty is estimated with a Dirichlet
405 distribution instead of bootstrapping (Steele 2005; Price, Wolfhagen, and
406 Otárola-Castillo 2016). While bootstrapping (i.e. sampling with replacement) can
407 be useful, it (i) assumes the age classes are independent, which is not the case
408 since a tooth can sometimes be assigned to more than one age class, while some
409 age classes are exclusive of each other; (ii) when the sample size is small, as is
410 typically the case in most archaeological assemblages, the bootstrap sample
411 mean may not converge to the true sample mean (Athreya 1987), and (iii) when
412 the sample size is small bootstrapping systematically under-represents variation.
413 Third, in contrast to the approach introduced by Price et al. (Price, Wolfhagen,
414 and Otárola-Castillo 2016), where the age class bin widths are equal, the
415 Bayesian method we propose conserves the relationship between survival rate
416 and the area under the survival curve since the age class bin widths depend on
417 their time span (e.g. Fries 1980). Fourth, our approach allows more flexibility
418 when comparing age-at-death frequency distribution, since multiple profiles can
419 be compared against each other rather than the comparison of one observed
420 profile against a reference profile (Price, Wolfhagen, and Otárola-Castillo 2016).
421 Alternatively, some archaeozoological studies have attempted to account for age
422 uncertainty and small sample size error using confidence intervals or standard
423 errors on age-at-death data (e.g. Tresset 1997; Valenzuela-Lamas et al. 2009).
424 However, these approaches have limited applicability since the data is not
425 normally distributed and age class frequencies are not independent. The
426 Dirichlet distribution is well suited for statistical assessment of such age-at-
427 death data as by definition it takes as parameters a vector of counts over
428 categories (Millard 2006). Our approach has the major advantage of accounting
429 for this sampling uncertainty, while accommodating all the information provided
430 by the observed sample. This is evident by the large credible intervals seen for
431 the infant/juvenile classes (Table 1 and Figure 2).

432 The age-at-death category divisions can lead to difficulties in interpreting
433 profiles because of (i) variations in the number of teeth in a hemi-mandible

434 according to the age of the animal (Masset 1973) and (ii) their unequal time
435 duration. While the former has mostly been ignored (probably due to challenges
436 raised by counting protocols issues), Helmer and Vigne (Helmer and Vigne 2004;
437 Vigne and Helmer 2007) attempted to solve the latter by introducing an “*a priori*
438 correction” of the relative frequencies, instead of the standard correction for
439 constructing the density histograms. This led to some misunderstanding by
440 scholars who did not account for the unequal probability of the age classes
441 (Greenfield 2005; Brochier 2013). The “*a priori* correction” is however not
442 appropriate, since it assumes that the age class frequencies are independent.

443 The final step in domesticate animal mortality analysis is the comparison of
444 multiple profiles from archaeological sites that differ in time period and/or
445 location of origin. The choice of statistical tests to compare age-at-death profiles
446 (Vigne 2000; Brochier 2013) and assess how significantly any two profiles may
447 differ (Marom and Bar-Oz 2009) have been debated intensively. For example,
448 some archaeozoologists (Tresset 1996; Vigne 2000; Helmer, Gourichon, and Vila
449 2007; Vigne 2011; Gillis 2012) proposed the use of multivariate differentiation
450 among age-at-death profiles based on correspondence analyses of the raw
451 frequencies of each age class. However, because of the high level of sampling
452 uncertainty in age-at-death data, we argue that none of the tests or distance
453 estimates proposed thus far in the archaeological literature are appropriate.

454 Correspondence analysis permits visualization of differences among age-at-
455 death profiles, and has the additional advantage of integrating the information
456 content of all 7 age classes (in contrast to triangular diagrams which use only
457 three age classes; (Greenfield 1988; Stiner 1990; Atıcı 2009)). None-the-less,
458 visual interpretation of how close age-at-death frequency distributions are,
459 based on a single point per age-at-death profile, is easily steered by subjective
460 biases (Brochier 2013) and not amenable to statistical assessment of these
461 differences. We have shown that generating a large set of random sample
462 deviates using the Dirichlet distribution, in combination to multivariate kernel
463 density estimation of these random deviates, permits robust comparison of age-
464 at-death profiles on correspondence analysis plots (Figure 3 and S1). However,
465 as noted above, it is important to consider all dimensions of variation in a

466 correspondence analysis and the contributions of the different age classes to the
467 analysis (Table S2).

468 We believe that the approach proposed here is novel in zooarchaeology and
469 constitutes a valuable addition to the age-at-death data analysis toolkit. Indeed,
470 we suspect that the approach proposed here will be useful in the analysis of
471 other categorical count data from archaeological sites, especially when sample
472 sizes are relatively small.

473 The approach proposed here does not solve all the challenges to analysing age-
474 at-death data. Robust consensual standards for age-at-death estimates, using, for
475 example, large modern reference collections for some domestic species, are still
476 required. In the introduction, we briefly argued for the use of dental age – using
477 the MNI or number of teeth as basic units of quantification – and of mortality
478 profiles rather than survival profiles; here again, the lack of consensual
479 standards has hampered development of age-at-death analysis techniques.

480 Frequency MNI (*sensu* Poplin (1976)) is replicable, but is not linearly correlated
481 with the absolute frequency. However, pairing MNI, used for elaborating age
482 profiles based on teeth, is often based on pairing right and left mandibles; which
483 may not be as replicable (Vigne 1988). Conversely, the number of teeth is a true
484 representation of the archaeozoological evidence. It is none-the-less subject to
485 the fragmentation-dissociation of teeth and to the initial number of teeth in the
486 mandible (Poplin 1976; Vigne 1988; Lyman 1994b). MNI are better adapted for
487 the less fragmented series of mandibles, whereas the number of teeth is much
488 suitable for series with numerous isolated teeth. Either frequency MNI and
489 number of teeth raw data are informative for addressing archaeozoological
490 debates (Vigne 1988).

491 Taphonomic loss is a direct outcome of site-specific depositional and post-
492 depositional histories (Brain 1981; Lyman 1987; Lyman 1994a; Halstead 1998)
493 and considerable challenges remain in assessing its effects. Taphonomic and
494 sampling biases, such as higher attrition caused by scavengers (Payne and
495 Munson 1985; Munson 2000) and differential survival or visibility of sub-adult
496 teeth (Lyman 1994a) may lead to observed age class profiles not representing
497 true age-at-death profiles at the time of deposition (Ducos 1988; Vigne 1988).

498 However, if these processes are similar at different sites then the approach we
499 describe here still permits relative comparison of observed site profiles. None-
500 the-less, the construction of credible intervals on mortality profiles improves our
501 confidence in interpreting the underlying management strategy.

502 4.2. A tentative interpretation of Cardial stock-keeping practices

503 This study primarily aims at introducing a novel statistical method to assess
504 mortality profiles from age-at-death data. This data is by nature scarce and
505 sample sizes typically small; the dataset presented here is no exception. Indeed,
506 while half of the sites are well dated and have good quality material (La Draga –
507 LAD, Grotte Lombard – GRO, Font Juvenal I – FON1, Combe Obscure I – COM1,
508 Baume d'Oulen I – BAU1), the others are either smaller samples from older
509 excavations (Cueva de la Sarsa – CUES, Abri I de Saint Mitre I – ASM1, Araguina-
510 Sennola – ARA1) with stronger taphonomic alterations (Abri II du Fraischamp –
511 ADF) and/or less accurately dated (Barret de Lioure – BAR; (Vigne 2007)). These
512 10 sites are therefore best thought of as a toy-dataset that is typical of other age-
513 at-death data generally used in archaeozoology. In order to explore the potential
514 power of the approach we develop here, we limited our analysis to those 10 sites
515 as they belong to a common Early Neolithic chrono-cultural entity (Cardial-
516 Epicardial), while showing some heterogeneity. Even though the aim of this
517 study is not to draw firm conclusions on Cardial herding strategies based on only
518 10 sites, some interesting observations can be made from the analyses
519 presented.

520 In the correspondence analysis presented in Figure 3a, we see that the profiles
521 are arranged according to a gradient (Guttman effect) following the succession of
522 the age classes from A to HI. However, in contrast to traditional analyses where
523 these two classes played an important role, they contribute little in the current
524 analyses (Table S2).

525 Figure 3b shows large overlaps in the density contours of five sites: Grotte
526 Lombard, Cueva de la Sarsa, Barret de Lioure, Abri de Saint Mître and Abri II de
527 Fraischamp. They cluster between the high frequencies of the C class (6-12
528 months) and D and E-F classes (12-48 months: adults). On the age-at-death
529 profiles (Figure 2) we see that three of these sites (Barret de Lioure, Abri de

530 Saint Mître and Abri II du Fraischamp), all located in Provence, display a similar
531 profile, with a clear dominance of class C. This pattern may correspond to mixed
532 milk and meat exploitation, with a dominance of tender meat production (Vigne
533 and Helmer 2007). The overlap of the profile of Grotte Lombard may be due to a
534 relatively even distribution of the frequencies between age classes (Figure 2);
535 this profile shows wider credible intervals, which may be due to the sample size.
536 Although Cueva de Sarsa overlaps with the other four sites (Figure 3b and S1), it
537 displays a slightly different profile (Figure 2) characterized by a well-
538 represented age class B, followed by age class C. This pattern indicates slightly
539 different practices, where younger individuals are more common, suggesting
540 lambs may have been removed early, and that an increase in milk production
541 was sought (Blaise 2005).

542 Located in Cataluña, La Draga plots apart, very near D and E-F with little overlap
543 except with Abri II of Fraischamp (Figure 3b). This site shows a narrow 95%
544 confidence interval, in line with its large sample size ($N_i=145$). This profile
545 (Figure 2) is dominated by age class D (12-24 months) with a secondary but
546 important contribution from E-F class (24-48 months). This could be interpreted
547 as indicating an overall meat exploitation (Vigne and Helmer 2007), with a
548 selective slaughtering of retired females, possibly for increasing lamb production
549 (and consequently milk?).

550 The three Languedoc cave sites plot at the other extremities of the gradient of
551 the Correspondence Analysis (Figure 3b). Combe Obscure stretches from B-C
552 (milk and tender meat) in the direction of HI, due to the relatively high
553 proportion of old adults (Figure 2); this can be due to hunting of feral sheep
554 (lower occurrence of flock leaders or old reproductive male). Baume d'Oulens
555 and Font Juvénil plot together and apart from the other sites due to their high
556 proportion of very young animals (class A), which may result from perinatal
557 mortality in the cave as they were used as sheep pen or due to a specialized
558 seasonal milk exploitation (Helmer et al. 2005; Vigne and Helmer 2007).

559 The only Corsican site (ARA1) plots in an intermediate position between the
560 three Provence shelter sites with tender meat exploitation (ASM, ADF1, BAR)
561 and the two Languedoc sites with specialized milk exploitation (FON1, BAU),
562 probably because of successive distinct occupation practices (Vigne 1988).

563 It is not possible to deduce the general pattern of exploitation practices of
564 caprines during the Early Neolithic from this small sample of heterogeneous
565 profiles. However, it seems that collectively they indicate distinct types of mixed
566 milk and meat exploitation. In addition, the inferred differences may represent
567 distinct regional strategies with more meat exploitation in the Provence sites
568 (ASM, ADF1, BAR), in contrast to a relatively higher tendency towards milk
569 production in the Languedoc sites (FON1, BAU, COM1). The two sites from
570 Catalunya and the one from Corsica show small differences with reference to
571 these sites.

572

573 5. FINAL COMMENTS

574 We introduce here a Bayesian approach to aid statistical comparison of
575 multivariate count data in archaeology. We exemplify this new approach on age-
576 at-death analysis for domestic animals using caprine toothwear data from 10
577 sites from the North Western Mediterranean Early Neolithic. Although our
578 dataset is small and disparate, some statistically robust patterns seem to emerge,
579 permitting a sketching of interesting geographical differences in herding
580 strategies. We suggest that the use of statistical approaches such as the Dirichlet
581 distribution will herald a new era in animal age-at-death analysis and husbandry
582 strategy reconstruction. Further large-scale analysis of sites from different time
583 periods and geographic locations should be performed to fully assess the power
584 of the approach suggested here in site comparisons.

585 While we have focused on data visualization using correspondence analysis,
586 there is also a clear need for the development of multivariate distance measures
587 to better assess relationships between age-at-death profiles at different sites;
588 such distance measures should lend themselves well to the analysis of the
589 Dirichlet population deviates generated as described here.

590

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