

1 **Marine resource reliance in the human populations of the Atacama Desert, northern**  
2 **Chile – a view from prehistory**

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17 All coauthors made substantial contributions to, and have approved the submission of this  
18 manuscript. Lead author CLK was responsible for study design, with advice from SEH and  
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20 information and insight into the regional archaeology. CLK undertook sample prep, samples  
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24  
25

## 26 **Abstract**

27

28 The Atacama Desert is one of the most inhospitable terrestrial environments on Earth, yet the  
29 upwelling of the Humboldt Current off the coast has resulted in the presence of a rich marine  
30 biota. It is this marine environment which first enabled the human settlement of the northern  
31 Atacama Desert, and continues to form the basis of regional economies today. In this paper  
32 we explore how the desert has shaped human dietary choices throughout prehistory, using  
33 carbon and nitrogen isotope analysis of human bone collagen (n=80) to reconstruct the diets  
34 of the inhabitants of the Arica region of the northern Atacama. This area is one of the driest  
35 parts of the desert, but has been generally understudied in terms of dietary adaptation.  
36 Statistical analysis using FRUITS has allowed deconvolution of isotopic signals to create  
37 dietary reconstructions and highlight the continued importance of marine resources  
38 throughout the archaeological sequence. Location also appears to have played a role in  
39 dietary choices, with inland sites having 10-20% less calories from marine foods than coastal  
40 sites. We also highlight evidence for the increasing importance of maize consumption,  
41 coinciding with contact with highland polities. In all periods apart from the earliest Archaic,  
42 however, there is significant variability between individuals in terms of dietary resource use.  
43 We conclude that marine resource use, and broad-spectrum economies persisted throughout  
44 prehistory. We interpret these results as reflecting a deliberate choice to retain dietary  
45 diversity as a buffer against resource instability.

46

47 **Keywords:** carbon; nitrogen; South America; dietary isotopes; FRUITS

48

## 49 **1. Introduction**

50

51 The Atacama Desert is one of the most extreme environments on Earth. As the driest hot  
52 desert in the world, life here is extremely marginal. Natural terrestrial resources are few, and  
53 freshwater availability is extremely limited (Williams et al., 2008). Human habitation of the  
54 desert, even today, is restricted to the valleys of the snowmelt-fed and seasonal rivers which  
55 traverse the Andean cordillera, and desert oases (Santoro et al., 2005). Yet, humans have  
56 occupied the desert for thousands of years (Arriaza et al., 2008). This is primarily due to the  
57 nearby marine environment. The Humboldt Current upwells off the north coast of Chile,  
58 bringing with it nutrient-rich waters and sustaining a rich and complex marine ecosystem  
59 (Thiel et al., 2007). The presence of plentiful marine resources meant that habitation of the  
60 desert was possible even prior to the adoption of agriculture, after which the ability to  
61 manipulate the desert environment began (Santoro et al., 2017).

62

63 In order to evaluate how different societies and natural environments affected diet in the  
64 Atacama Desert, however, there is a need for palaeodietary data from multiple parts of the  
65 desert, and different time periods. Palaeodietary work already undertaken in the Atacama  
66 Desert suggests, relatively unsurprisingly, that human subsistence choices were constrained  
67 by the desert environment (Santana-Sagredo et al., 2015; Torres-Rouff et al., 2012). There is  
68 evidence from the incipient agricultural sites (dating from 1700BC) of coastal valleys of  
69 extreme northern Chile, such as Pampa Tamarugal and the Loa River Valley, that during the  
70 transition to agriculture, desert populations retained significant marine-resource input into  
71 their diet (Bonilla et al., 2016; Pestle et al., 2015a; Santana-Sagredo et al., 2015; Torres-  
72 Rouff et al., 2012). This has been interpreted as reflecting the presence of trade networks  
73 (Pestle et al., 2015a; Pestle et al., 2015b) to mitigate the instability of terrestrial crops through  
74 use of marine resources (Santana-Sagredo et al., 2015). While trade networks developed  
75 during the Formative Period (*ca.* 1700BC - 450AD), these socio-economic interactions

76 continued during all subsequent periods, allowing some areas to become focused on maize  
77 agriculture and camelid pastoralism (e.g. Pestle et al., 2016; Torres-Rouff et al., 2015). Other  
78 regions seemed to have retained broad-spectrum based subsistence despite being influenced  
79 by polities whose dietary focus was maize (Knudson et al., 2007), such as the Tiwanaku,  
80 Wari (*ca.* 450–900AD) and later Inka peoples (1450–1600AD). These polities whose  
81 homelands were in the Peruvian highlands, expanded and annexed surrounding areas in the  
82 Middle Period (Wari and Tiwanaku) and Late Period (Inka). While there has, in the past,  
83 been a strong focus on the impact of these external polities and their reliance on maize in the  
84 Atacama Desert, it is becoming increasingly recognised that this crop has played a variable  
85 role in the subsistence economies of the desert people (Cuéllar, 2013; Tykot et al., 2006).  
86 Similarly, the role of different ecological niches in subsistence decisions is just beginning to  
87 be explored in the region (Zaro, 2007).

88

89 To date there have been relatively extensive isotopic studies of diet conducted in the San  
90 Pedro de Atacama and Tarapacá regions, but there is a dearth of data from the Arica region.  
91 These areas, while all located in the Atacama Desert, have quite different local environments,  
92 and therefore the potential for different subsistence choices in prehistory. For instance, the  
93 desert varies quite considerably in terms of freshwater availability and therefore suitability  
94 for human habitation and agriculture. In San Pedro de Atacama, in inland northern Chile for  
95 example, archaeological sites are centred around the natural oases. Agriculture was possible  
96 in this area (Llagostera and Costa, 1999; Nuñez, 2007) and it was likely an important  
97 stopping point for camelid traders moving from the political centres of the Andean highlands  
98 (Hubbe et al., 2012; Kolata, 1991; Llagostera, 1996). In Peru there are fog ‘oases’ in the  
99 desert, providing moisture which increases floral variability (Beresford-Jones et al., 2015)  
100 and the potential for agricultural yields (Sandweiss et al., 1999). The desert in the Tarapacá

101 and Arica regions, however is extremely dry, experiencing less than 0.6 mm of rain per year  
102 (Williams et al., 2008). Agriculture even today is possible in very restricted areas centering  
103 around the river valleys and inland oases.

104

105 As well as geographic variation in water availability, there has also been climatic variation in  
106 rainfall over time. The El Niño southern oscillation has serious effects on the amount of  
107 rainfall in any given year, and El Niño cycles have varied in intensity throughout prehistory  
108 (Gayo et al., 2012; Moseley and Keefer, 2008; Sandweiss et al., 2009). Around 500 BC, for  
109 example, palaeoclimatic data suggest a change to El Niño regime, resulting in higher levels  
110 of humidity in the Atacama Desert (Gayo et al., 2012), and considerably expanding the  
111 agriculture land available. During this time period archaeological evidence suggests the  
112 development of extensive field systems alongside villages such as Ramaditas, Guatacondo  
113 and Caserones (Uribe and Vidal, 2012; Vidal et al., 2012), located in harsh environments  
114 where today agriculture is not possible. In these sites, remains of *Zea mays*, *Phaseolus*  
115 *lunatus*, *P. Vulgaris*, *Lagenaria*, *Arachis hypogaea*, *Chenopodium quinoa* and Algarrabo  
116 (*Prosopis*) pods have been identified (McRostie et al., 2017; Santoro et al., 2017). These  
117 plants are not endemic to the northern Atacama and it is likely that they were introduced from  
118 the Andes and the eastern lowlands. This research aims to assess both the impact of the  
119 arrival of these crops, and the marginality of the desert environment on resource choices.

120

121

## 122 **2. Environmental context: Arica region**

123

124 The Arica region has four snowmelt-fed rivers, the Lluta, San Jose, Chaca and Camarones  
125 (Fig. 1). Further to the south it is more truly arid, with the Loa River and its tributaries

126 providing some of the only freshwater (Santoro, 2012). Use of the terrestrial environment in  
127 the Arica region, however, is further complicated by the presence of high levels of  
128 contaminating heavy metals (arsenic, lithium and boron) in the rivers (Apata et al., 2017;  
129 Figueroa et al., 2012). This means that while there is freshwater, its use and consumption can  
130 have serious health implications (Arriaza et al., 2010; Swift et al., 2015).

131

132 **Fig 1.** Location of the study area and surrounding regions. Inset gives study site locations and  
133 occupation periods with the Azapa valley expanded for clarity.

134

135 Dietary adaptations in the Arica region have not yet been investigated using isotopic  
136 techniques, but instead inferred using archaeological evidence. Archaeological evidence  
137 suggests that marine resource consumption was fairly ubiquitous throughout prehistory, with  
138 marine faunal remains and material culture associated with fishing found even in interior  
139 valley sites (Table 1). From around 7000 BC the area played host to a large Archaic period  
140 population of *Chinchorro* marine hunter-gatherers, who settled the coast and relied heavily  
141 on the ocean for all sustenance (Arriaza et al., 2008; Standen et al., 2017). From 1700 BC,  
142 however, there appears to have been a change in the El Niño regime, resulting in depression  
143 of the fisheries, relocation of the coastal peoples into inland river valleys, and the beginnings  
144 of agriculture in the region (Grosjean et al., 2007; Moreno et al., 2009; Williams et al., 2008).  
145 The cultivation of the interior valleys will have provided the people of the region with the  
146 ability to produce staple terrestrial crops for the first time. Andean domesticates such as  
147 potato (*Solanum*), ullucu (*Ullucus*), and quinoa (*Chenopodium*) become common in the  
148 archaeological record (Pearsall, 2008). Later in prehistory the region begins to interact with  
149 highland Andean polities such as the Tiwanaku (Muñoz, 1983; Muñoz, 1995), eventually  
150 being annexed by the Inka Empire in the Late Period (Santoro et al., 2010). These cultures

151 would have allowed resource trade with other parts of their empires, as well as having  
152 specific ideas surrounding diet. In particular, both the Tiwanaku people and the Inka Empire  
153 placed ceremonial importance on the consumption of maize (Goldstein, 2003; Staller, 2010).  
154 There is ethnographic and archaeological evidence that, despite the marginality of  
155 agricultural land, the area became significant for maize production under the Inka Empire  
156 (Murra, 1980; Santoro et al., 2010).

157

158 In this study we investigate the effect of the desert environment on prehistoric resource-use in  
159 the Arica region. We hypothesise that the marginality of the desert means that ancient  
160 populations are unlikely to have relied solely upon agricultural resources in any period.  
161 Instead a sustained reliance on marine resources is likely. The ocean has always been a  
162 plentiful source of food, leading to a maritime tradition which persists even into the present  
163 day. We therefore examined diet in coastal and near-coastal valley sites from both  
164 agricultural and pre-agricultural periods to examine whether or not dietary diversity, and  
165 marine resource use, is maintained throughout prehistory. We then compare the isotopic data  
166 to other lines of archaeological evidence relating to resource use to build a fuller picture of  
167 subsistence strategies in the region.

168

### 169 **3. Archaeological context**

170

171 The studied samples derive from archaeological sites in the northern Atacama Desert, close  
172 to the modern-day city of Arica (Fig. 1). Sites lie both on the coast, and in the near-coastal  
173 areas of the Azapa Valley. This region has a long human occupation history, but not all  
174 periods and cultures are present both inland and on the coast. For example, the Archaic  
175 period is not well-represented in the inland valleys. Conversely there is a lack of evidence for

176 Middle Period occupation of the coast (Muñoz, 1982; Sutter, 2000). The known prehistoric  
177 cultural sequence is therefore briefly described here.

178

179 *Archaic Period:*

180 The first evidence for human settlement of the Arica region is between 9400–8200 BC  
181 (Arriaza et al., 2008; Moreno et al., 2009), and corresponds with the presence of small  
182 communities of hunters, fishers, and collectors well adapted to exploitation of the marine  
183 ecosystem. Most bioarchaeological and archaeological evidence suggests that Chinchorro  
184 populations were almost completely reliant upon the marine environment for subsistence  
185 (Arriaza et al., 2017; Aufderheide et al., 1993). However, Holden (1994) and Reinhard et al.  
186 (2011) have both reported possible cases of potato starch and quinoa seeds in Chinchorro  
187 coprolites at Morro 1/6 site, suggesting the inhabitants harvested and consumed wild plants.  
188 By 5000 BC these coastal populations developed extraordinary funerary practices including  
189 artificial mummification that lasted until ca. 1500–1000 BC (Arriaza, 1995; Standen et al.,  
190 2014; Standen, 2003). These dates mark the end of the Chinchorro cultural tradition and also  
191 the transition towards food production in the coastal valleys of the Arica region (Grosjean et  
192 al., 2007; Santoro et al., 2017).

193

194 *Formative Period:*

195 Although fisher-gatherer populations continue to live on the coast during the following  
196 Formative Period, for example at the site of Quiani (ca. 1500–1600 BC), there is evidence  
197 that plants such as squash and gourds were being incorporated into mortuary rituals. Recent  
198 studies show there is a correlation between edible plants offered as grave goods in the  
199 prehistoric sites of the Arica region, the species identified in human dental calculus (as  
200 phytoliths and starch grains) and the frequency of dental caries (Arriaza et al., 2017).



201 Archaeological evidence suggests that later Formative Period coastal groups like Faldas del  
202 Morro (800 BC) had strong links to the inland valley sites and were incorporating agricultural  
203 products in their diet (e.g. (Belmonte, 1998; Erices, 1975).

204

205 There is however, much that remains unknown regarding the development of early farming  
206 cultures in the Arica region. While Formative coastal populations were incorporating  
207 agricultural products into their diets, it is probable that they maintained marine specialization,  
208 with terrestrial products forming only a very small portion of dietary intake. Indeed, most  
209 coastal sites are dominated by objects associated with maritime subsistence: hooks, harpoons,  
210 fishing lines, hook weights (Muñoz, 1993; Muñoz and Focacci, 1985). Inland sites also retain  
211 material culture associated with fishing, indicating that marine resources remained important  
212 (Santoro, 1980b). This is counter to traditional archaeological interpretations which have  
213 inferred that inland Formative sites are much more reliant upon agricultural resources.

214

215 The first farmers of the inland Azapa Valley sites have generally been associated with the  
216 Alto Ramírez cultural Phase, which according to Rivera (Rivera, 1994; Rivera, 1975)  
217 corresponds with a migration from the complex Formative centres of the highlands, such as  
218 Wankarane and Pukara down to the coastal valleys. This diffusionist model reflects  
219 archaeological paradigms which tended to try to establish cultural dependency between the  
220 marginal societies of the coastal valley in the Atacama Desert and the large power centers of  
221 the highlands. Although other studies (Muñoz, 2004; Núñez and Santoro, 2011) have  
222 highlighted the important and active role that local populations played during the Archaic-  
223 Formative transition, there must have been some exogenous contributions in this process. The  
224 first agricultural crops grown in the area are not endemic to the region and must have been  
225 brought in either through trade or movement of peoples or both. It is therefore possible that

226 the inland valley populations of the Arica region will have had a diet based upon terrestrial  
227 resources and buffered by exchange networks which extend to the highlands, as interpreted  
228 by Pestle et al. (2015a) further to the south.

229

230 *Middle Period:*

231 There is also debate in the archaeological literature over the extent to which the Arica region  
232 was involved in the expansion of highland polities (such as Tiwanaku and Wari) during the  
233 Middle Period. Traditionally the presence of Tiwanaku-style ceramics, particularly vessels  
234 (*queros*) used for the consumption of chicha (maize beer) has been used as evidence for these  
235 sites coinciding with the Middle Period (AD 450–900). However, there has been debate over  
236 the level to which groups were influenced by these polities. In the Arica region two cultural  
237 groups seem to have been present; Maytas and Cubuza, with Cubuza groups more influenced  
238 by the Tiwanaku. In this study we focus on the Cubuza sites as representative of the Middle  
239 Period. However, recent radiocarbon-dating of mortuary offerings in some of these Cubuza  
240 sites, has revealed them to belong to the Late-Intermediate Period (AD 900–1450), rather  
241 than the earlier Middle Period (Korpisaari et al., 2014). It is possible that Tiwanaku presence  
242 and influence in the Arica area was the result of political collapse in the Bolivian highlands,  
243 and displacement of peoples into the Northern Chilean valleys, rather than deliberate  
244 annexation during the height of Tiwanaku power (Korpisaari et al., 2014). Nonetheless, the  
245 importance of maize in the Tiwanaku culture is often inferred to have had an impact in the  
246 sites of the Arica region (Muñoz, 1983).

247

248 *Later periods:*

249 The foundation of maize agriculture laid by the Middle Period polities is usually assumed to  
250 have been elaborated by cultural groups during the Late-Intermediate Period (AD 900–1450),

251 culminating in the ritualised maize consumption that characterises the Late Period and  
252 associated Inka state (AD 1450–1600)(Goldstein, 2003; Staller, 2010). The cultivation and  
253 consumption of chicha underlay most social and ritual transactions during the Inka period,  
254 and was symbolically associated with imperial power (Bauer, 1996; Goldstein, 2003; Staller,  
255 2010).

256

257 *Chronology of sites used in this study*

258

259 The dating of sites in the Arica region has been conducted somewhat haphazardly, and  
260 sometimes more recent radiocarbon dates directly contradict earlier dates (Korpisaari et al.,  
261 2014; Muñoz, 2017; Sutter, 2005). It was not possible to take radiocarbon samples for this  
262 project, we therefore use a combination of existing radiocarbon data and artefactual evidence  
263 for cultural affinity to assign sites used to archaeological phase. For instance, we consider  
264 sites with Tiwanaku pottery as representing the Middle Period, because their subsistence  
265 regime is likely to have been affected by Tiwanaku cultural values, similarly sites with Inka  
266 influence (i.e. the Camarones sites) are likely to have been influenced by Inka maize-reliance.

267

268 Table 1 gives the sites used in this study, their assigned phase and the rationale for that  
269 assignment. The focus of this isotopic study, however, is not chronologically constraining  
270 differences in subsistence choices, but instead understanding how the desert environment  
271 affected resource use during prehistory as a whole. Our analysis and interpretation does not  
272 look at change through time, but instead considers differences between inland and coastal  
273 sites, and sites with evidence for interaction with highland polities and those without.  
274 Diversity in resource use, or lack thereof, within and between sites will give us insight into

275 resource-use choices regardless of chronological gaps and issues with the construction of  
276 cultural sequences.

277

278 *[Table 1 near here]*

279

## 280 **4. Materials and Methods**

281 Analysis of stable carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) isotopic ratios from human collagen  
282 provide an insight into the diet of past human society. In particular, it is possible to  
283 differentiate marine from terrestrial resource use, the photosynthetic pathways of plant  
284 resources used, and the trophic level of food indicating meat consumption or the type of  
285 marine resources exploited (Ambrose and Norr, 1993; Schoeninger and DeNiro, 1984).  
286 Carbon isotopes are fractionated differently according to plant photosynthetic pathway ( $\text{C}_3$   
287 vs.  $\text{C}_4$ ), with  $\text{C}_3$  plants favouring fixation of lighter  $^{12}\text{C}$  more than  $\text{C}_4$  plants do resulting in a  
288 more negative  $\delta^{13}\text{C}$  value (Ambrose and Norr, 1993). In the Atacama Desert, crops such as  
289 quinoa, tubers and pulses (e.g. beans) are  $\text{C}_3$  crops, and are differentiable from the  $\text{C}_4$  crop,  
290 maize (which is less  $^{12}\text{C}$ -enriched). Carbon isotopes may also be used to highlight marine  
291 resources, with marine carbonate concentrating  $^{13}\text{C}$ , resulting in less negative  $\delta^{13}\text{C}$  values in  
292 in comparison to  $\text{C}_3$  plants (Chisholm et al., 1982).

293

294 Nitrogen isotopic ratios vary with trophic level, and each step up the food chain increases  
295  $\delta^{15}\text{N}$  values between 2‰ and 6‰ (DeNiro and Epstein, 1981; O'Connell et al., 2012). This  
296 means that broadly speaking, in the absence of aquatic resource consumption,  $\delta^{15}\text{N}$  values  
297 can be related to levels of terrestrial meat consumption. However, as marine food-chains tend  
298 to involve more steps, consumption of high trophic level marine resources results in  
299 especially high  $\delta^{15}\text{N}$  values (Fry, 2006; Minagawa and Wada, 1984).  $\delta^{15}\text{N}$  values in Atacama

300 Desert terrestrial foodchains are also enriched in  $^{15}\text{N}$  relative to other areas of the world (Díaz  
301 et al., 2016). This is a result of the aridity of the environment and resulting differences in  
302 nitrogen cycling (Ehleringer et al., 1992). Arid conditions result in the volatilisation of  
303 nitrogen compounds such as ammonia and this process preferentially involves the light  
304 isotope  $^{14}\text{N}$ , thus concentrating  $^{15}\text{N}$  in soils and foliage (Amundson et al., 2003), an  
305 enrichment which is carried through terrestrial food-chains (Gröcke et al., 1997; Hartman,  
306 2011).

#### 307 **4.1 Materials**

308 This study involved the sampling and isotopic analysis of adult individuals from the  
309 archaeological collections of the Museo Arqueológico San Miguel de Azapa (MASMA),  
310 Arica. The samples derive from the archaeological sites of the Azapa and Camarones river  
311 valleys, and the coastal sites of Arica (Fig. 1). Sites and numbers of individuals sampled are  
312 listed on Table 1, a complete list of individuals sampled is given in Table S1. MASMA  
313 enforces strict sampling regulations to preserve their collections. The sampling of bone was  
314 therefore restricted to 25 adult individuals from each phase. Collagen was assessed using  
315 Durham University Archaeology laboratory protocols and was considered to be of good  
316 quality if: C/N ratio = 2.9–3.6 and 35–50% carbon and 11–16% nitrogen (e.g. (DeNiro,  
317 1985). A number ( $n = 13$ ) of individuals from the Archaic phase sampled had poor  
318 preservation of collagen, with the collagen extracted not passing standard quality control  
319 checks (see S1 Table). After excluding those with poor quality collagen the analysed sample  
320 set comprised of 80 individuals. The poor preservation of collagen in the Archaic samples has  
321 been previously documented in this region (Aufderheide et al., 1993; Silva-Pinto et al.,  
322 2014), and persists despite repeat preparation procedures and addition of a filtration step to  
323 the protocol. Sampling was restricted to individuals who were not artificially mummified,

324 ensuring that some bone was exposed and available for analysis. Only adults were sampled in  
325 this study to ensure all individuals were completely weaned and the isotopic signatures  
326 represent an adult diet. This work on adult diet, however, will form an important baseline for  
327 future work looking at infant diet and weaning patterns.

## 328 **4.2 Methods**

329 Skeletal sex estimation was undertaken by the authors [CK and VS] using the standards in  
330 Buikstra and Ubelaker (1994). Individuals were assigned to age groups (Young, Middle, Old)  
331 using standard scoring of the pubic symphysis (Brooks and Suchey, 1990) and auricular  
332 surface (Lovejoy et al., 1985), with epiphyseal fusion taken into account in the case of young  
333 adults (Buikstra and Ubelaker, 1994).

334 Samples of bone weighing between 100–200 mg were taken using a diamond cutting wheel.  
335 These were removed from already fragmented and disarticulated ribs to avoid unnecessary  
336 damage to any skeletal elements or mummified material. Adhering particulates were removed  
337 through surface abrasion with a diamond burr. Prior to collagen extraction a defatting  
338 procedure equivalent to those used in analysis of modern bone was employed (O'Connell et  
339 al., 2001). The samples were rinsed in deionised water then sonicated in test tubes containing  
340 a 2:1 methanol:chloroform solution for 2 hours, with the solvent changed every 30 minutes.  
341 Bone fragments were then prepared following a modified Longin (Longin, 1971) method i.e.  
342 demineralised in 0.5M HCl, gelatinised in a pH3 HCl solution at 75°C overnight, centrifuged  
343 and decanted to remove particulates, then lyophilised.

344

345 Total organic carbon, total nitrogen content and stable isotope analysis of the samples was  
346 performed using a Costech Elemental Analyser (ECS 4010) connected to a Thermo Delta V  
347 Advantage isotope ratio mass spectrometer. Carbon isotope ratios were corrected for <sup>17</sup>O

348 contribution and reported in standard delta ( $\delta$ ) notation in per mil (‰) relative to Vienna Pee  
349 Dee Belemnite (VPDB). Isotopic accuracy was monitored through routine analyses of in-  
350 house standards, which were stringently calibrated against international standards (e.g.,  
351 USGS 40, USGS 24, IAEA 600, IAEA N1, IAEA N2): this provided a linear range for  
352 calibration in  $\delta^{13}\text{C}$  between  $-46.7$  ‰ and  $+2.9$  ‰ and in  $\delta^{15}\text{N}$  between  $-4.5$  ‰ and  $+20.4$  ‰.  
353 Analytical uncertainty in carbon and nitrogen isotope analysis was typically  $\pm 0.1$  ‰ for  
354 replicate analyses of the international standards and typically  $< 0.2$  ‰ on replicate sample  
355 analysis (see S1 Table). Total organic carbon and nitrogen data were obtained as part of the  
356 isotopic analysis using an internal standard (Glutamic Acid, 40.82 % C, 9.52 % N).

357

358 The statistical software R (R core team, 2013) was used to script and visualise our data. In an  
359 effort to increase the reproducibility of research (Marwick, 2017) .csv files and R scripts used  
360 in this analysis have been made available via a GitHub repository  
361 ([https://github.com/DrCharlieKing/Atacama\\_Bulk](https://github.com/DrCharlieKing/Atacama_Bulk)). Values from modern terrestrial flora and  
362 fauna data were corrected for the Suess effect to pre-industrial levels (Long et al., 2005)  
363 using data from Francey et al. (1999). There is also a systematic offset between human  
364 collagen values and those of the diet consumed. When presenting human data with foodweb  
365 data this dietary offset is corrected for by shifting human values to those of their diet, to  
366 allow easier visualisation of possible dietary components. There is debate over the exact  
367 magnitude of this offset (O'Connell et al., 2012), but here we use controlled feeding data and  
368 consider the  $\delta^{13}\text{C}$  diet-collagen offset as  $4.8 \pm 0.5$  ‰, and  $\delta^{15}\text{N}$  diet-collagen offset as  $5.5 \pm$   
369  $0.5$  ‰ (Fernandes et al., 2012; Froehle et al., 2010; Huelsemann et al., 2009).

370

371 In the Atacama Desert there are a number of resources that overlap substantially in terms of  
372 isotopic signatures, for example less negative  $\delta^{13}\text{C}$  values may represent  $\text{C}_4$  crop or marine

373 resource consumption. Although analysis of dental enamel carbonate ( $\delta^{13}\text{C}_{\text{apatite}}$ ) could  
374 potentially resolve these interpretive issues, sampling restrictions prevented this being  
375 undertaken as a part of this study. Instead, quantitative dietary reconstruction was undertaken  
376 using a Bayesian mixing model – Food Reconstruction Using Isotopic Transferred Signals  
377 (FRUITS) (Fernandes et al., 2014), in order to account to some extent for dietary routing and  
378 offsets.

379

380 FRUITS allows the estimation of the contribution of different food sources to the diet using  
381 measured isotopic values and food source data (Fernandes et al., 2014). It takes into account  
382 dietary routing (i.e. the preferential use of certain dietary components in specific tissues) and  
383 isotopic offsets, and allows the incorporation of *a priori* assumptions. In this study we used a  
384 weighted and concentration-dependant model, considering the input of both the protein and  
385 energy components of the diet in the consumer isotopic values. The main FRUITS model  
386 used is given as Supplementary File 1. Mean values for each of the phases were used to  
387 model group diet, although we also present results from individuals to demonstrate the  
388 heterogeneity in diet within single sites. We considered the input of four dietary sources:  $\text{C}_3$   
389 plants,  $\text{C}_4$  plants, terrestrial meat and marine meat (including shellfish, fish and marine  
390 mammals). Food source values were derived from previously conducted isotopic work in the  
391 Northern Atacama (Cadwallader et al., 2012; DeNiro and Hastorf, 1985; Szpak et al., 2012;  
392 Tieszen and Chapman, 1992) that is summarised in Andrade et al. (2015). Weighting of the  
393 model was based upon previous work detailing average nutrient contribution of the different  
394 food groups to human diet (Fernandes et al., 2015), with plant cereals protein:  $10 \pm 2.5$  wtC  
395 %; carbs/lipids:  $90 \pm 2.5$  wtC %, terrestrial meat sources:  $30 \pm 2.5$  wtC %; carbs/lipids:  $70 \pm$   
396  $2.5$  wtC % and marine foods:  $35 \pm 5$  wtC %; carbs/lipids:  $65 \pm 5$  wtC %. We also follow  
397 Fernandes et al. (Fernandes et al., 2015; Fernandes et al., 2014) in using the *a priori*



398 assumption that overall dietary protein intake will involve protein carbon contribution of  
399 between 5–45 % (Otten et al., 2006). In addition, the Archaic Period reconstructions included  
400 the prior that C<sub>4</sub> resources form the least important component of diet, as there are no  
401 endemic C<sub>4</sub> resources in the Arica region, and therefore it is not until the Formative Period  
402 that we would expect these to become a possible important component of diet. Isotopic  
403 offsets were defined using the same controlled-feeding experiment data as used to plot our  
404 data ( $\delta^{13}\text{C}$  diet-collagen offset =  $4.8 \pm 0.5$  ‰,  $\delta^{15}\text{N}$  diet-collagen offset =  $5.5 \pm 0.5$  ‰)  
405 (Fernandes et al., 2012; Froehle et al., 2010; Huelsemann et al., 2009).

406

407 To test the robustness of dietary reconstructions alternative models using different dietary  
408 information and parameters were also run, and their results compared to our primary model.  
409 The first of the alternative dietary scenarios involved the inclusion of fertilised C<sub>4</sub> plant data  
410 (see Supplementary File 2). The fertilization of maize with seabird guano was a common  
411 agricultural practice during the Late Period (Julien, 1985), and results in elevated  $\delta^{15}\text{N}$   
412 values, such that fertilised maize overlaps isotopically with high trophic level marine  
413 resources (i.e. marine carnivores such as sealions). In our model we have considered guano  
414 fertilization a possibility from the Middle Horizon onwards, as the earliest archaeological  
415 evidence for potential deliberate use of guano is from this period (Kelley et al., 1991; Muñoz  
416 and Focacci, 1985). The inclusion of this data in our model allows us to quantify the potential  
417 confounding effects of fertilization on our data. In addition, three other model types were run:  
418 1) removing *a priori* assumptions (Supplementary File 3); 2) with offsets altered by  $\pm 1$  ‰  
419 (Supplementary Files 4 and 5); and 3) with food values altered by  $\pm 1.5$  ‰ (Supplementary  
420 Files 6-9). Dietary reconstructions are considered robust if these changing parameters did not  
421 result in significant changes to dietary contribution estimates.

422

## 423 5. Results

424

425 The results of carbon and nitrogen isotopic analysis are given with reference to local foodweb  
426 data in Fig. 2, and are reported in full in Table S1.

427

**Fig. 2:** Isotopic baseline data plotted alongside average human dietary values for each phase (with 95% confidence ellipses). Human isotopic values have been corrected for the diet-tissue offset (as described in-text). Datapoints represented by squares (rather than circles) are individuals representing the ‘extremes’ of dietary variation in each phase. These individuals have associated individual FRUITS dietary reconstructions (Fig. 4).

428

### 429 5.1 FRUITS dietary estimates

430

431 Fig. 3 presents the dietary reconstructions generated by our main FRUITS model for each for  
432 each archaeological period. The estimated contributions of each food source, and  
433 uncertainties associated with these estimates are also given in Table 2.

434

435 **Fig. 3:** FRUITS model output for each archaeological phase. Box and whisker plots (left)  
436 represent credibility intervals, with boxes representing a 68% credible interval, and whiskers  
437 a 95% credible interval. Horizontal lines represent the mean and median (dashed and  
438 continuous lines respectively). Probability distributions (right hand figures, y-axes) are given  
439 for each of the contribution estimates (x-axes).

440

441 *[Table 2 near here]*

442

443 As Fig. 2 and high standard deviations in Table 2 show, there are relatively high levels of  
444 dietary variability in each of the phases. We acknowledge that the individuals grouped in  
445 archaeological phases may not be contemporaneous and therefore directly comparable due to  
446 the long occupation period of some sites. To fully describe the variation present, even within  
447 one site, we have generated FRUITS estimates of dietary contributions for individuals  
448 representing the extremes of diet in each phase (individuals marked as squares on Fig. 2). The  
449 Archaic Period is excluded from this individual analysis due to the small sample size and  
450 relative homogeneity of diet in this phase.

451

452 These individual results are presented in Fig. 4 and Table 3.

453

454 *[Table 3 near here]*

455

456 **Fig. 4:** FRUITS model output for each archaeological phase. Boxes represent 68% credible  
457 intervals, and whiskers 95% credible intervals. Horizontal lines represent the mean and  
458 median (dashed and continuous lines respectively).

459

## 460 **5.2 Robustness and accuracy of dietary estimates**

461

462 The dietary inputs calculated by the alternative models are given in supplementary tables S2-  
463 4. Each of the modelled dietary scenarios have similar probability distributions associated  
464 with different food sources (% input), although the actual percentages vary with the changing  
465 model parameters. Each dietary scenario has associated uncertainties ranging between 2 and  
466 20 %, with the majority of uncertainties being under 15 %. These uncertainties are not large

467 enough to change the overall interpretation of which resources are contributing the most to  
468 diet in each of our phases.

469

470 In most of the modelled dietary scenarios, despite the reconstructed % contributions to diet  
471 changing, the overall reconstruction of which resources contribute more or less to diet  
472 remains the same. For example, the Archaic estimates always show that marine food makes  
473 up the majority of the diet, with C<sub>4</sub> resources comprising only a small portion. In the  
474 Formative period it is terrestrial resources which make up the bulk of the diet, in particular C<sub>3</sub>  
475 plants. In the later phases C<sub>4</sub> plants form the foundation of the diet, although in the coastal  
476 Late Period sites marine resources form an equally important portion. Interestingly the  
477 inclusion of guano fertilised maize data (i.e. C<sub>4</sub> crops with significantly higher  $\delta^{15}\text{N}$ ) from the  
478 Middle Period onwards does not significantly affect model outcomes (S4 table). Estimated  
479 dietary contributions in the guano-fertilised model differ by 2–6 % from the main model  
480 presented in this paper.

481

482 The removal of prior assumptions from the model does significantly affect percent  
483 contribution estimates in the Archaic, with a change to estimated C<sub>4</sub> contribution of 18 %.  
484 Aside from large changes to the Archaic Period estimates when priors are removed, the  
485 majority of other models run change the percent contribution estimates by no more than 6 %.  
486 This extreme change in the Archaic is due to the removal of the prior assumption that C<sub>4</sub>  
487 resources will comprise the smallest contribution to diet, due to lack of endemic C<sub>4</sub> plants.  
488 Other phases did not include this prior due to the presence of C<sub>4</sub> resources introduced from  
489 the highlands.

490

491 **6. Discussion**

492

493 The results of analysis using FRUITS clearly support the hypothesis that marine resources  
494 remained an important dietary component throughout the prehistory of the Arica region. In  
495 addition, they highlight that proximity to the coast, perhaps unsurprisingly, has the most  
496 significant impact on the level to which marine resources are consumed, though they are a  
497 consumed in all sites regardless of time period or cultural affiliation. The arrival of maize and  
498 increasing importance of this resource from the Middle Period onwards is also visible  
499 isotopically. Here we discuss the persistence of marine resource use through time, the  
500 retention of broad-spectrum subsistence strategies and geographic constraints on resource  
501 use, and the possible influence of maize-reliant polities on subsistence in the region.

502

503 **6.1 Continued consumption of marine resources despite the arrival of agricultural**  
504 **resources**

505

506 The results of FRUITS analysis clearly indicate the continued consumption of marine  
507 resources throughout prehistory in the Arica region. In sites closest to the coast i.e. those  
508 from the Archaic and Late periods, marine resources provide around 40 % of caloric input,  
509 although some individuals within those sites appear to have had a marine input closer to 60  
510 %. Most archaeological models assume the arrival of agriculture in the Formative Period  
511 involved an increase in terrestrial resource consumption, and this is borne out by our data  
512 which suggests that terrestrial resources do provide more caloric input during these periods.  
513 Marine resources, however, continue to comprise between 15–20 % of the diet. This aligns  
514 well with isotopic research in other parts of the Atacama Desert which has shown the  
515 persistence of marine resource use in both coastal and inland sites during the Formative  
516 Period (Andrade et al., 2015; Pestle et al., 2015a; Santana-Sagredo et al., 2015).

517

518 In addition, within each agricultural archaeological period analysed in this study there  
519 remains variation in marine resource consumption, with some individuals obtaining up to 68  
520 % of their calories from the ocean (e.g. Az141 T10 in the Formative Period). This is a higher  
521 contribution even than the most extreme values from coastal sites in this study.

522

## 523 **6.2 The importance of the environment – coastal vs. inland sites**

524

525 In this sample over all periods and locations we see that resource decision-making is clearly  
526 affected by geographic availability, particularly relating to proximity to the coast. In our  
527 sample the sites located on the coast (i.e. the Archaic Morro sites and Late Period Camarones  
528 sites), unsurprisingly, consumed the most marine resources. There is no statistically  
529 significant difference in marine resource consumption between the Archaic and Late Period  
530 sites, but there are statistically significant differences between all inland (Formative, Middle  
531 and Late-Intermediate) sites and coastal (Archaic and Late) sites. This reflects the persistence  
532 of a marine tradition which is present even today in the modern cities of the coastal desert.

533

534 Inland sites, however, have approximately 20 % less caloric input from marine food sources  
535 than those at the coast. This is not necessarily as expected, as all sites analysed are within a  
536 day's walk from the coast, and marine resource gathering requires less energy input than  
537 rearing livestock or cultivating crops. There is, in addition, no correlation between absolute  
538 distance from the coast and marine input into the diet. Formative sites included in this study  
539 are the closest valley sites to the coast, yet display the least marine resource use. Middle  
540 Period sites analysed here are 10–15 km further from the coast, but use the most marine  
541 resources of all of the agricultural periods. Instead we consider it more likely that the inland

542 sites, in general used less marine resources but the specific amounts used will have been  
543 dependent upon climatic conditions affecting the fisheries. Prevailing archaeological models,  
544 for example, predict that the initial move inland during the Formative Period was precipitated  
545 to changes to El Niño intensity which dramatically depressed the fisheries (de Bryson et al.,  
546 2001; Muñoz and Chacama, 2012). It is perhaps unsurprising then that we see the least use of  
547 marine resources in these earliest agricultural sites. Climatic oscillations during site  
548 occupation may also be responsible for the high levels of ‘within site/phase’ variation in  
549 isotopic results we see. Small-scale variations in El Niño cycles are likely to have caused  
550 differences in the availability of resources throughout prehistory. Individuals within the same  
551 site may have experienced quite different resource pressures, even generation to generation,  
552 if water availability changed or marine upwelling was affected. Thus the variation in marine  
553 resource use may not have been personal choice or culturally-mediated, but instead  
554 environmentally-dictated.

555

### 556 **6.3 The importance of maize and links to external polities**

557

558 It has been generally assumed that maize played a more important role in subsistence from  
559 the Middle Period onwards, due to the presence of maize-reliant polities such as the  
560 Tiwanaku (Middle Period) and the Inka state (Late Period) (Goldstein, 2003). This does  
561 appear to be the case in the study sample, as C<sub>4</sub> contribution to the average diet increases  
562 dramatically between the Formative (24 %) and Middle Horizon (46 %), with C<sub>4</sub> contribution  
563 to diet remaining high throughout the subsequent archaeological phases. Even in coastal Late  
564 Period sites, where marine resources are likely to have been much easier to access, C<sub>4</sub>  
565 consumption provides a reasonable proportion of total caloric input (39 %).

566

567 However, it should be noted that maize consumption in the Arica region never reaches the  
568 calculated levels of other areas annexed by or in contact with these same polities. For  
569 example, in the Ayacucho Valley of Peru, dietary isotope analysis has suggest that maize  
570 provided around 70% of dietary protein (Finucane, 2009). It is possible that the geographic  
571 location of the Azapa Valley, away from major centres of Tiwanaku and Inka control, meant  
572 that there was less cultural importance placed on maize consumption in this area (e.g. (King  
573 et al., In review).

574

#### 575 **6.4 Linking isotopic and archaeological evidence for subsistence strategies**

576

577 Overall the FRUITS reconstructions align well with archaeological evidence for subsistence.  
578 The dietary reconstructions presented here, however, also go some way to resolving  
579 archaeological questions about the importance of different resource types in each site. For  
580 example, archaeozoological and material culture evidence for marine resource consumption  
581 is present in all inland sites analysed (Focacci, 1990; Santoro, 1980a; Valenzuela et al.,  
582 2015), but it is difficult to know how important these resources were. Our results show that  
583 not only were marine resources present they also comprised an important part of the diet,  
584 although the input into individuals' diet was variable.

585

586 The variety of crop species and subsistence tools found even at inland agricultural sites may  
587 be used to infer that life in the Azapa Valley was never focussed on a single crop or  
588 subsistence strategy (Muñoz, 1987; Valenzuela et al., 2015). Our isotopic results support this  
589 interpretation, showing that the average diet during the Formative Period involved roughly  
590 equal proportions of C<sub>3</sub> and C<sub>4</sub> plants, terrestrial meat and marine resources. Even extreme  
591 individuals in this phase, who relied more upon one resource type than the others, still seem



592 to have been consuming small proportions of other resource types. There is archaeological  
593 evidence for an increase in maize consumption in the Middle Horizon and Late-Intermediate  
594 Periods in that maize remains and material culture associated with chicha consumption  
595 become ubiquitous in sites (Muñoz and Focacci, 1985; Muñoz and Zalaquett, 2015). Our  
596 isotopic results corroborate the idea that maize becomes more important, as in both the  
597 Middle Horizon and Late-Intermediate periods C<sub>4</sub> resources are the most important dietary  
598 component. They are not, however, solely relied upon, and indeed there are some individuals  
599 for whom they form a much lesser proportion of the diet.

600

601 Archaeological research has previously questioned the importance of maize at Late Period  
602 coastal sites despite Inka cultural involvement. At sites such as Camarones maize cannot be  
603 grown locally and archaeobotanical evidence indicates that chicha (traditionally a maize  
604 beer), appears to have been made primarily from C<sub>3</sub> crops rather than maize (Arriaza et al.,  
605 2017; Arriaza et al., 2016). Our research indicates that maize is likely to have formed an  
606 important component of the diet despite its lack of inclusion in chicha. In fact, the C<sub>3</sub> crops  
607 from which chicha was apparently made do not generally contribute much to diet. It is  
608 possible that the use of these crops in chicha was more an expression of local identity while  
609 under Inka rule, than an indication of lack of maize availability.

610

## 611 **6.5 Variation in isotopic results, and diet in general, from each phase**

612

613 Isotopic results from the inland Formative, Middle and Late-Intermediate Periods are  
614 extremely variable. Perhaps the most extreme example of this variation comes from  
615 Formative Period Az14, where individuals at one extreme appear to be consuming almost  
616 exclusively C<sub>3</sub> plants, while others seem to have a diet dominated by marine protein. It is

617 tempting to interpret this isotopic variation within archaeological phases or single sites as  
618 evidence for heterogeneous diet between contemporary individuals. Unfortunately, however,  
619 the ambiguity of site dating in the Arica region means that individuals within the same site  
620 are not necessarily contemporaneous. Instead, this variation may indicate generational  
621 changes to diet, perhaps reflecting cyclical resource availability due to El Niño oscillations,  
622 or cultural change resulting in the changing popularity of some resources. Future work  
623 involving the tightening of site chronologies may reveal systematic temporal changes to diet  
624 within phases, that are currently not interpretable.

625

## 626 **6.6 Differences between FRUITS dietary reconstructions and previous modelling in the** 627 **region**

628

629 One of the major differences between the dietary reconstructions generated in this study and  
630 those attempted previously (Aufderheide et al., 1994; Aufderheide et al., 1993) is the percent  
631 input of marine resources estimated. The linear mixing models in these studies have predicted  
632 up to 80 % of dietary protein was derived from marine resource consumption. We anticipate  
633 that this difference is partly due to our use of Bayesian rather than simple linear mixing  
634 modelling, but is also because our FRUITS model used metabolic experimental data to define  
635 the acceptable intake of dietary protein. As a result of this our dietary reconstructions seem to  
636 align better with archaeological evidence for subsistence than earlier estimates. For example,  
637 while marine resources undoubtedly formed the most significant portion of Archaic diet there  
638 is evidence from Archaic coprolites of C<sub>3</sub> plants and terrestrial meat (Reinhard et al., 2011).  
639 Our dietary reconstructions support this idea of terrestrial resource use, and reduce estimates  
640 of percent contribution of marine resources to what we consider more reasonable levels.

641

## 642 **7. Conclusion**

643

644 The isotopic results presented here paint a picture of deliberate retention of dietary diversity  
645 in the peoples of the Atacama Desert. The marine resource use traditions begun by the  
646 Archaic *Chinchorro* peoples persist throughout prehistory and into the modern day, with use  
647 of the rich marine environment buffering the desert populations against terrestrial resource  
648 insecurities. While the arrival of maize-reliant polities does seem to have had an impact on  
649 subsistence in later archaeological phases, agricultural crops are never fully relied upon.  
650 Instead geographic constraints, such as proximity to the ocean, seem to have had a greater  
651 impact on overall diet. Our results also highlight dietary diversity both within and between  
652 archaeological phases, potentially relating to changes to resource availability and El Niño  
653 cycles.

654

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656

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668

669

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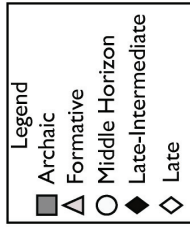
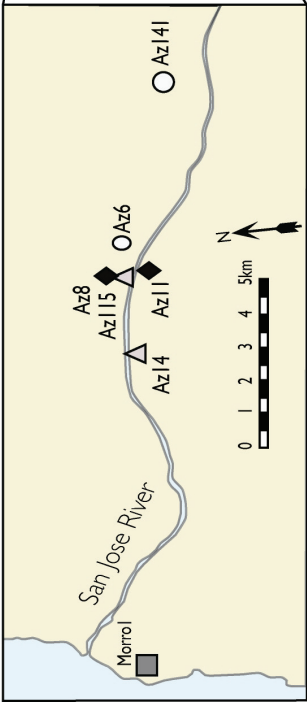
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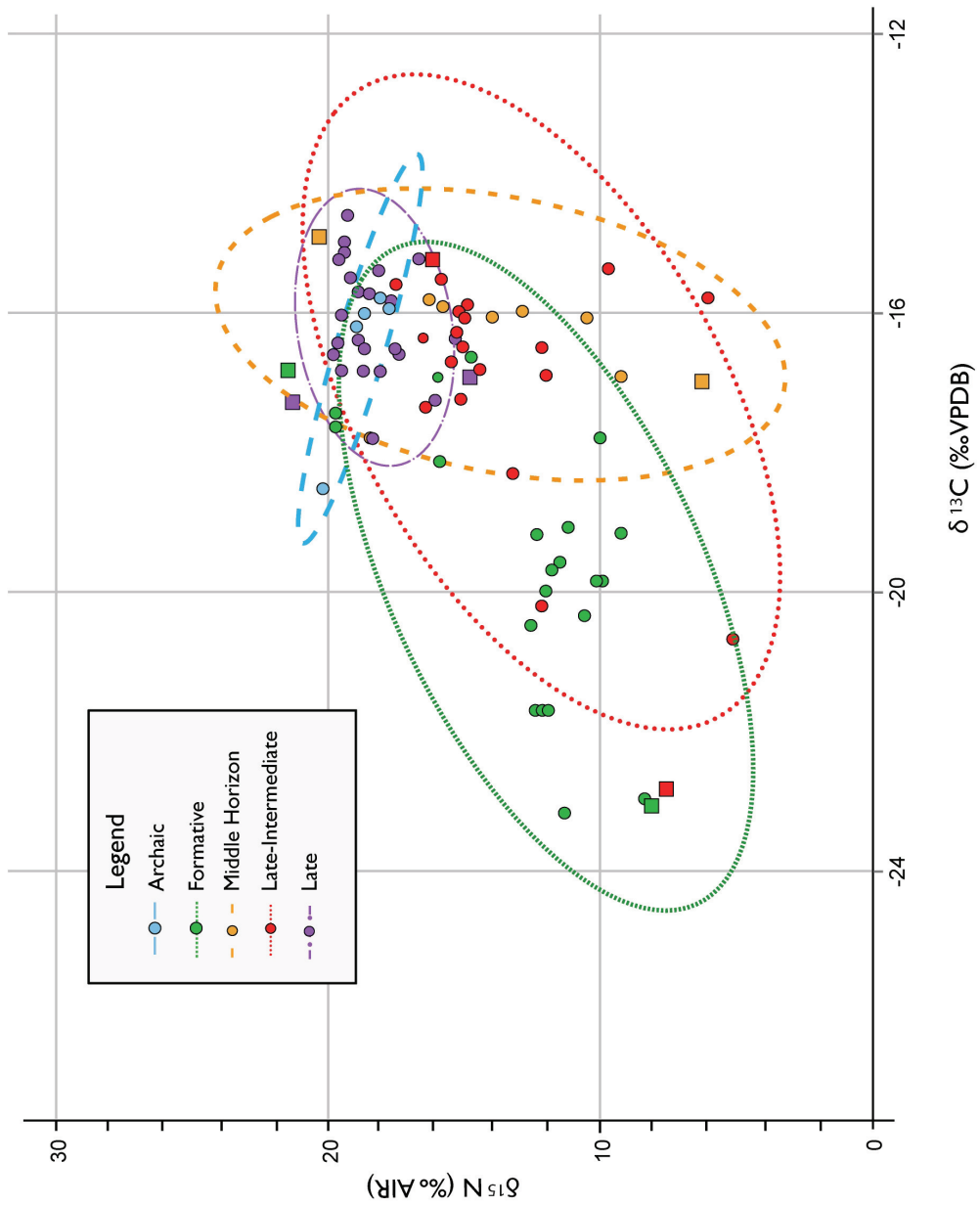
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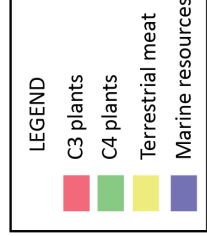
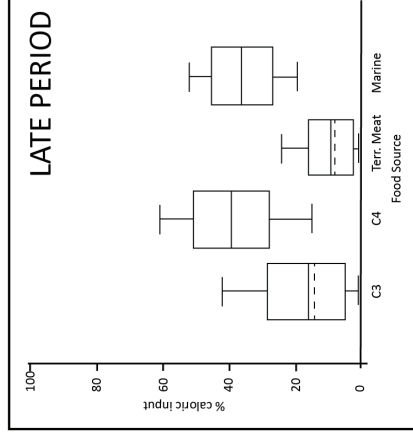
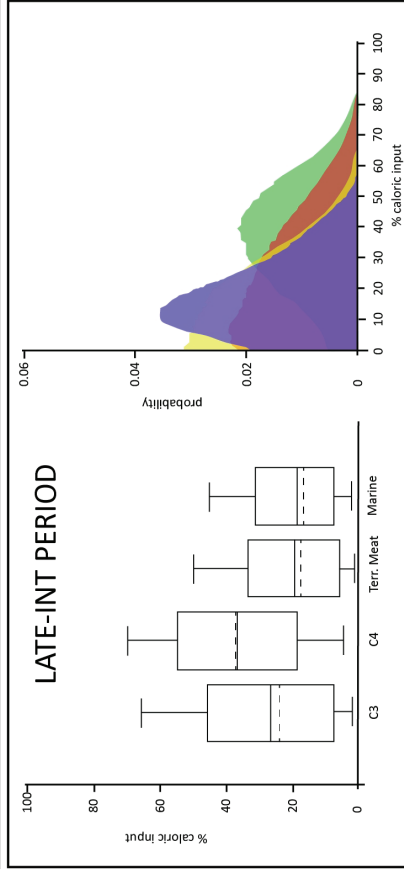
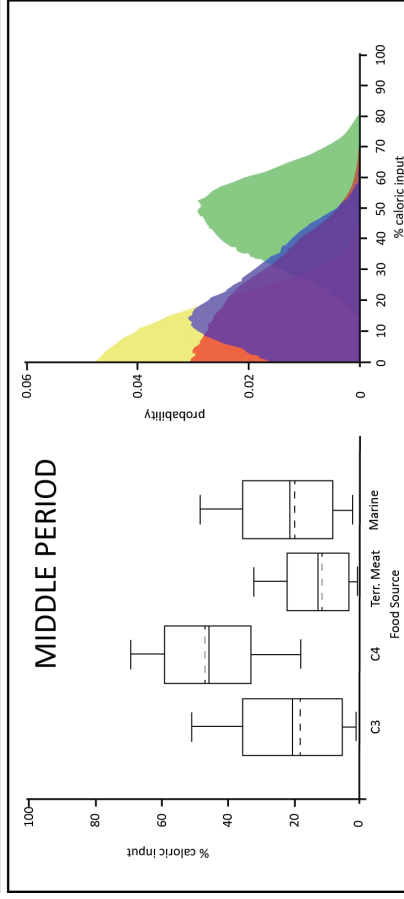
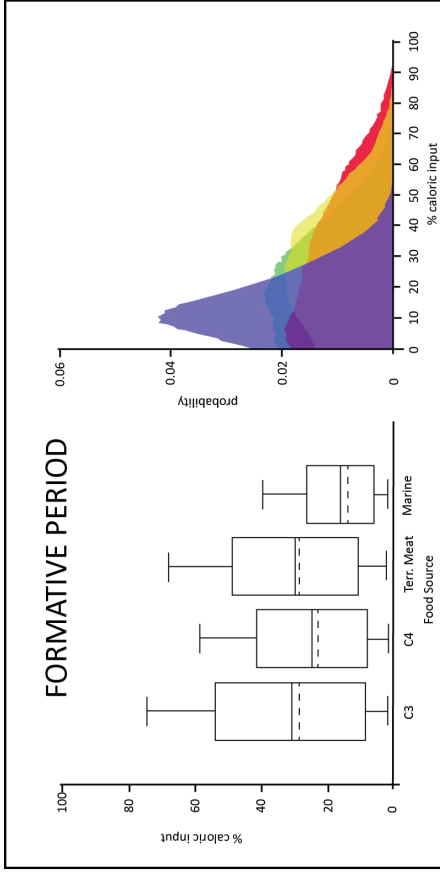
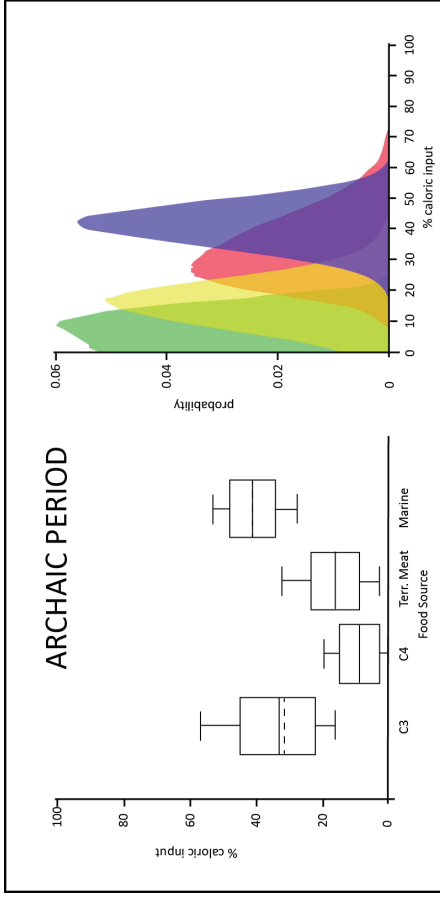
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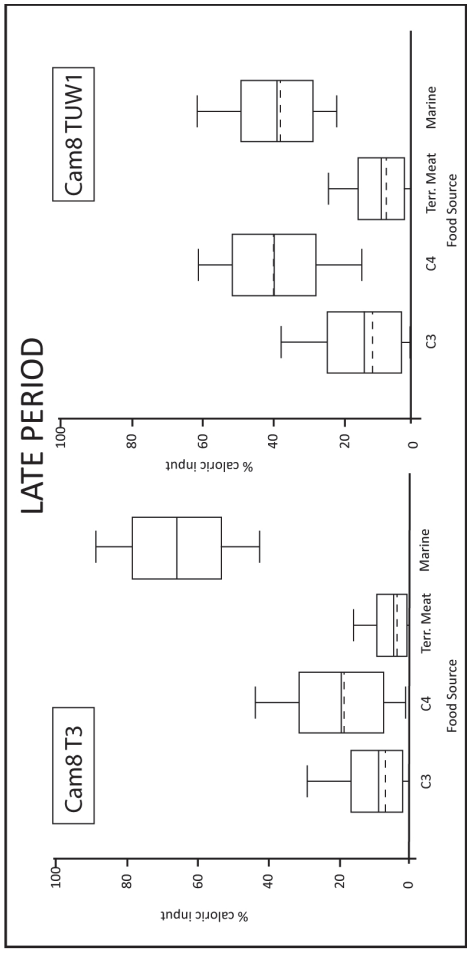
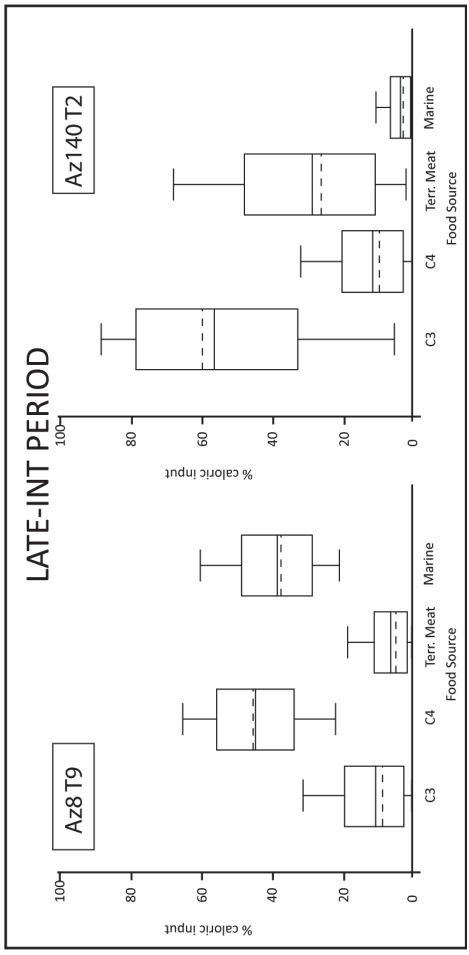
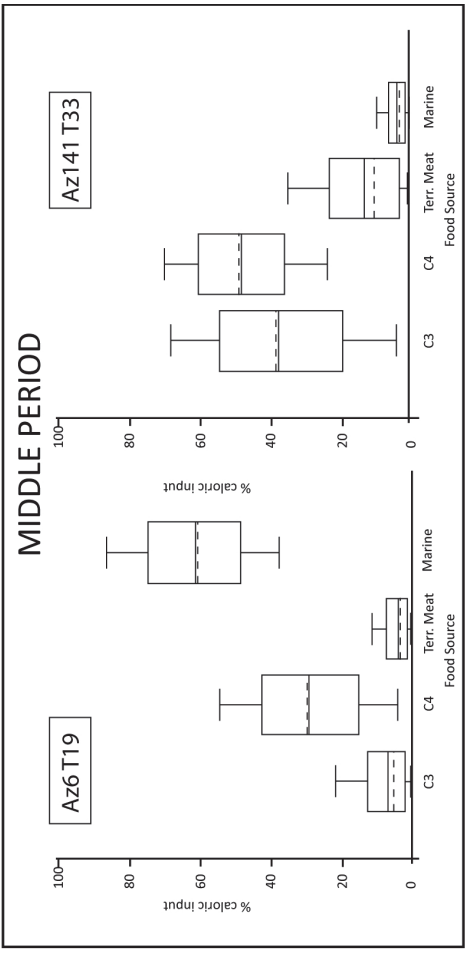
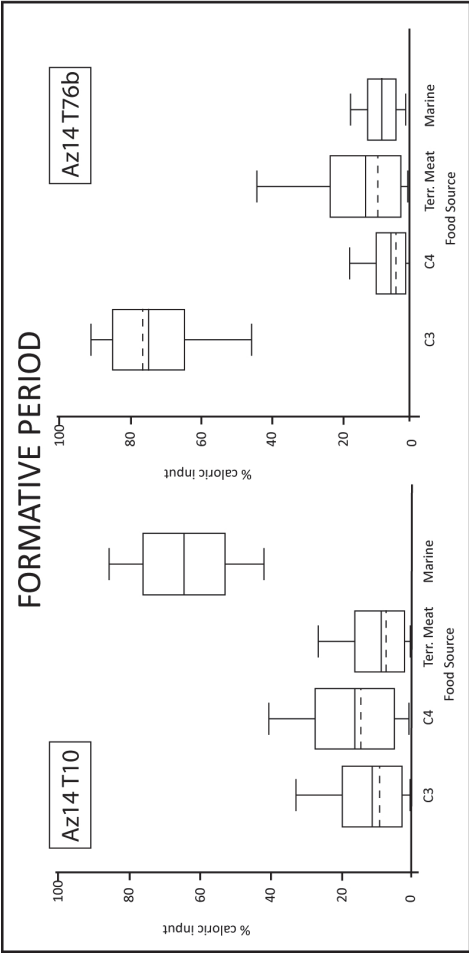
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	Archaeozoological/ botanical remains	Subsistence related material culture	Inferred subsistence strategy from archaeological evidence	Site dates (dating method)	Time period	Reason	Number of individuals sampled
Morro 1	Molluscs, crustaceans, seaweed, fish, marine mammals and birds, few camelid bones and skins (Standen, 2003). Plant fibre present in coprolites (Reinhard et al., 2011)	Harpoons, fishhooks, nets, ropes, 'chopes' (shellfish processing tools), spear, bows, darts, projectile points (Standen, 2003)	Marine hunter- gatherer	6226 – 1748 cal BC. (Allison et al., 1984)  2917 cal BC (Standen, 1991)  (radiocarbon dates on burials)	Archaic	Radiocarbon dates.	5
Az115	Curcubita, maize, tubers camelids, dog, guinea pig, birds, fewer fish and marine mammal bones (Muñoz Ovalle, 2017)	Darts, spear tips, slings	Broad-spectrum agriculturalists	100-600AD  (radiocarbon dates on burials)	Late Formative	Radiocarbon dates. Although some recent dates place some burials in the Middle Period (Muñoz Ovalle, 2017) there are no Tiwanaku cultural features.	14
Az14	Shellfish, fish, guinea pig, maize, quinoa,	Chopes, bows, wooden points,	Broad-spectrum agriculturalists	900-560BC uncalibrated	Formative	Radiocarbon dates	8

	manioc, camote (Santoro, 1980a)	harpoons (context uncertain)(Santoro, 1980a)		(Santoro, 1980b; Santoro, 1982)	Middle Horizon – Late Intermediate	Both Tiwanaku and Cabuza pottery present.	5
Az141				1044-1290 cal. AD (Korpisaari et al., 2014) 890+/- 100 AD (Schiappacasse et al., 1991) 1018-1276 AD (Sutter, 2005)			
Az6	Maize, camote, squashes, coca, dog, guinea pig, llama, shellfish/shells, birds (Focacci, 1990)	Wooden digging/tiling sticks, bows, arrows, quivers,	Agro-pastoralists	380 AD (Focacci, 1990) 890 – 1392AD (Focacci Aste, 1982) 850-1350 AD (Korpisaari et al., 2014)	Middle Horizon – Late Intermediate	Both Tiwanaku and Cabuza ceramics and other items of material culture present.	5
Az11	Camelids, dogs, guinea pigs, 1x monkey, birds, rodents, maize, beans, squashes, camote, manioc,	Arrowheads, darts, hoes, sticks, wooden shovels, harpoons,	Agro-pastoralists	790-980AD (Muñoz Ovalle and Focaccia, 1985)	Middle Horizon	Radiocarbon dates BUT Maytas pottery (not Tiwanaku)	5

Az8	potato, quinoa, molluscs, fish, freshwater snails.	chopes, fishhooks.		1,150 – 1,350AD (Rothhammer and Santoro, 2001) 910AD – 1120AD (Espouey's et al., 1995) 500-890AD(Núñez, 1976)	Late-Intermediate	Radiocarbon dates	13
Cam8	Maize, sweet potato, manioc, squash, beans, quinoa, camelids, dogs, fish, marine mammals (Muñoz, 1989)	Wooden shovels, harpoons, arrowheads	Marine subsistence complemented by agricultural crops	1050-1560AD (Thermoluminescence of potsherds) (Schiappacasse et al., 1991)	Late	Inka pottery, textiles	10
Cam9	Birds, sealions, sea turtle, fish, shellfish, camelids, maize, squashes (Ulloa et al., 2000)	Harpoons, bows, darts, oars, fishhooks,	Marine subsistence complemented by agricultural crops.	1050-1560AD (Thermoluminescence of potsherds) (Schiappacasse et al., 1991)	Late	Inka textiles (Ulloa et al., 2000)	15

**Table 1:** Sites sampled in this study, geographic location, archaeologically-inferred subsistence regime and assigned time period with reasoning and key primary data sources

<b>Phase</b>	<b>C<sub>3</sub> input</b>	<b>C<sub>4</sub> input</b>	<b>Terrestrial meat input</b>	<b>Marine input</b>
Archaic	32 ± 10	10 ± 5	17 ± 7	41 ± 6
Formative	31 ± 21	24 ± 16	30 ± 18	15 ± 10
Middle Horizon	20 ± 14	46 ± 13	13 ± 9	21 ± 13
Late-Intermediate	24 ± 17	38 ± 16	20 ± 14	18 ± 12
Late	16 ± 11	39 ± 12	9 ± 7	36 ± 9

**Table 2:** % total caloric contribution to diet of each food source as reconstructed by FRUITS analysis. Errors given are 1SD.



<b>Time period</b>	<b>Individual</b>	<b>C<sub>3</sub> input</b>	<b>C<sub>4</sub> input</b>	<b>Terrestrial meat input</b>	<b>Marine input</b>
Formative	Az14 T10	9 ± 7	16 ± 9	7 ± 6	68 ± 9
	Az14 T76b	83 ± 6	3 ± 2	6 ± 5	8 ± 3
Middle	Az6 T19	6 ± 5	29 ± 13	3 ± 2	62 ± 13
	Az141 T33	37 ± 17	48 ± 12	12 ± 10	3 ± 2
Late Intermediate	Az8 T9	7 ± 6	51 ± 7	4 ± 3	38 ± 7
	Az11 T16	63 ± 16	9 ± 6	25 ± 14	3 ± 2
Late	Cam9 T59	8 ± 6	23 ± 10	3 ± 2	66 ± 11
	Cam8 TUW1	10 ± 8	46 ± 8	7 ± 4	37 ± 8

**Table 3:** % total caloric contribution to diet of each food source for selected individuals, as reconstructed by FRUITS analysis. Errors given are 1SD.

Sample	period	Sex	Age	C/N	C wt %	$\delta^{13}\text{C}$ (‰ PDB)	N wt %	$\delta^{15}\text{N}$ (‰ AIR)
M1 T3	Archaic	F?	old?	3.8	33.7	-12.4	10.2	24.5
M1 T4	Archaic	M	young	3.4	45.0	-11.1	15.4	23.4
M1 T6	Archaic	U	U	3.5	45.6	-11.2	15.2	23.1
M1 T7	Archaic	M	U	4.0	31.9	-14.6	9.8	28.3
M1 T10a	Archaic	M	mid	3.4	42.5	-11.5	14.6	24.3
MI T12	Archaic	M	young	3.4	37.4	-11.3	13.0	24.0
M1 T15	Archaic	F	old	3.2	27.4	-12.8	10.0	24.8
M1 T16b	Archaic	M?	mid?	3.9	26.1	-13.4	9.5	25.0
M1 T18c2	Archaic	U	U	3.9	45.3	-14.0	13.6	21.8
M1 T19c1	Archaic	M	young	3.7	32.3	-12.3	10.1	25.0
M1 T22c5	Archaic	F	mid	-	-	-	-	-
M1 T23c3	Archaic	M?	young-mid	-	-	-	-	-
M1 T23c12	Archaic	F?	young	-	-	-	-	-
MI T23c13	Archaic	F	young	3.5	45.6	-13.8	15.2	25.5
M1 T27c5	Archaic	M	young	4.0	28.5	-12.8	8.5	23.9
M1 T27c11	Archaic	M?	young-mid	-	-	-	-	-
M1 T28c12	Archaic	M?	U	-	-	-	-	-
M1-6 T19	Archaic	U	U	3.7	28.1	-12.8	8.8	23.9
Az115 Museo C4	Formative	M?	U	-	-	-	-	-
Az115 Museo C7	Formative	U	U	3.8	42.2	-16.3	13.0	16.0
Az115 S/R1	Formative	U	U	3.3	43.8	-15.1	15.5	15.3
Az115 T3b (BN294)	Formative	M?	mid	3.3	40.4	-15.8	14.3	17.9
Az115 T5	Formative	M	young-mid	3.3	41.7	-14.8	15.0	16.8
Az115 T8	Formative	F	mid	3.5	44.3	-13.1	14.9	15.5
Az115 T9	Formative	F?	young-mid	3.2	38.3	-15.1	13.8	15.4
Az115 T11	Formative	F	mid	3.6	47.0	-15.6	15.3	15.9

Az115 T16a	Formative	M	young		3.3	41.3	-13.4	14.7	21.3
<b>Az115 T16b</b>	<b>Formative</b>	<b>M</b>	<b>mid</b>		-	-	-	-	-
<b>Az115 T17a</b>	<b>Formative</b>	<b>M</b>	<b>mid-old</b>		-	-	-	-	-
AZ115 T17b	Formative	F	mid		3.3	42.2	-14.9	14.8	17.1
AZ115 T18	Formative	M	mid		3.4	44.4	-14.3	15.5	16.5
AZ115 T19	Formative	M	mid		3.6	44.7	-15.2	14.7	17.3
AZ115 T21	Formative	F	mid		3.4	45.7	-14.2	15.6	14.7
AZ115 T22	Formative	M	young-mid		3.4	44.2	-11.9	15.3	20.0
AZ115 T25	Formative	F	young-mid		3.3	41.7	-14.4	14.7	17.7
AZ115 T26	Formative	M	young-mid		3.5	44.3	-13.1	14.9	15.5
AZ14 ent1	Formative	M	U		3.6	32.8	-12.7	10.7	25.0
AZ14 TX	Formative	F?	young		3.5	38.3	-18.4	12.7	16.7
AZ14 T1	Formative	M	mid		3.3	39.8	-17.0	14.1	17.4
AZ14 T1 F15	Formative	F	young		3.3	42.8	-17.0	15.1	17.6
AZ14 T7	Formative	F	old		3.4	44.5	-18.3	15.6	13.6
AZ14 T10	Formative	M	young-mid		3.2	42.5	-11.8	15.7	25.5
AZ14 T14	Formative	F	young		3.6	42.2	-17.0	13.8	17.8
<b>Az14 T59</b>	<b>Formative</b>	<b>M</b>	<b>young</b>		-	-	-	-	-
<b>Az14 T64c</b>	<b>Formative</b>	<b>M</b>	<b>U</b>		-	-	-	-	-
<b>Az14 T66</b>	<b>Formative</b>	<b>M</b>	<b>U</b>		-	-	-	-	-
<b>Az14 T69</b>	<b>Formative</b>	<b>M</b>	<b>mid</b>		-	-	-	-	-
AZ14 T76b	Formative	M?	young		3.5	43.3	-18.2	15.5	13.7
<b>Az6 MCA3</b>	<b>Middle Horizon</b>	<b>F</b>	<b>mid</b>		-	-	-	-	-
<b>Az6 T6</b>	<b>Middle Horizon</b>	<b>F</b>	<b>young</b>		-	-	-	-	-
Az6 T19	Middle Horizon	F	young		3.3	42.1	-10.2	14.7	25.7
<b>Az6 T22 G1/1</b>	<b>Middle Horizon</b>	<b>F</b>	<b>mid-old</b>		-	-	-	-	-
<b>Az6 T25 H1/1</b>	<b>Middle Horizon</b>	<b>M</b>	<b>young</b>		-	-	-	-	-

<b>Az6 T26 H1/2</b>	<b>Middle Horizon</b>	<b>F</b>	<b>young-mid</b>	-	-	-	-	-	-
Az6 T36 J2/1	Middle Horizon	M	young	3.4	40.9	-11.2	14.2	21.1	-
Az6 T41b	Middle Horizon	M	mid	3.3	42.7	-11.4	14.9	20.4	-
<b>Az6 T48 K1/2</b>	<b>Middle Horizon</b>	<b>F</b>	<b>U</b>	-	-	-	-	-	-
Az6 T71 M5/2	Middle Horizon	M	young	3.4	43.0	-11.4	14.8	15.9	-
Az6 T116 R3/2	Middle Horizon	M	mid	3.4	42.0	-11.1	14.6	21.6	-
Az141 Des02	Middle Horizon	F	mid	3.5	38.6	-13.4	12.8	23.9	-
Az141 T22	Middle Horizon	M	mid	3.2	37.4	-12.2	13.5	14.6	-
Az141 T23	Middle Horizon	U	U	3.6	44.1	-11.3	14.4	18.2	-
<b>Az141 T26</b>	<b>Middle Horizon</b>	<b>M</b>	<b>young</b>	-	-	-	-	-	-
Az141 T33	Middle Horizon	M	mid-old	3.2	33.2	-12.3	12.0	11.7	-
<b>Az141 T36</b>	<b>Middle Horizon</b>	<b>M</b>	<b>young</b>	-	-	-	-	-	-
<b>Az141 T37</b>	<b>Middle Horizon</b>	<b>F</b>	<b>mid</b>	-	-	-	-	-	-
Az141 T52	Middle Horizon	M	young-mid	3.4	41.1	-11.3	14.3	19.2	-
<b>Az141 T53</b>	<b>Middle Horizon</b>	<b>M</b>	<b>young</b>	-	-	-	-	-	-
Az11 T3	Late-Int	F	old	3.4	47.0	-14.9	15.9	10.7	-
<b>Az11 T7a</b>	<b>Late-Int</b>	<b>M</b>	<b>young-mid</b>	-	-	-	-	-	-
Az11 T7	Late-Int	F	mid	3.6	43.3	-11.8	14.1	17.6	-
Az11 Sec T8	Late-Int	F	mid-old	3.4	42.3	-11.1	14.7	11.6	-
Az11 T16	Late-Int	M	mid	3.4	42.6	-17.8	14.6	11.8	-
Az8 T5b	Late-Int	F	mid	3.3	42.5	-10.8	15.0	21.2	-
Az8 T7a	Late-Int	M?	young	3.4	41.2	-12.0	14.0	20.9	-
<b>Az8 T7b</b>	<b>Late-Int</b>	<b>M</b>	<b>young-mid</b>	-	-	-	-	-	-
Az8 T9	Late-Int	F	young	3.5	44.3	-10.6	14.6	21.6	-
Az8 T13	Late-Int	M	young	3.4	43.5	-11.3	14.9	20.4	-
<b>Az8 T19</b>	<b>Late-Int</b>	<b>F</b>	<b>mid</b>	-	-	-	-	-	-
<b>Az8 T23</b>	<b>Late-Int</b>	<b>F</b>	<b>mid-old</b>	-	-	-	-	-	-

Az8 T24	Late-Int	F	mid-old	3.2	41.6	-12.1	15.1	19.8
Az8 T25	Late-Int	M	young-mid	3.5	39.7	-11.8	13.3	20.4
Az8 T30	Late-Int	F	young	3.5	44.8	-11.6	15.1	20.7
Az8 T31	Late-Int	F	young	3.4	42.2	-12.2	14.7	17.4
Az8 T35	Late-Int	M	young	3.5	44.0	-11.2	14.5	20.3
Az8 T38	Late-Int	F	young	3.4	41.6	-12.2	14.3	20.1
Az8 T40	Late-Int	F	young-mid	3.4	43.7	-10.7	15.1	15.2
<b>Az8 T41</b>	<b>Late-Int</b>	<b>F</b>	<b>young-mid</b>	-	-	-	-	-
Az8 T42	Late-Int	M	young	3.6	44.3	-15.5	14.5	17.5
<b>Az8 T43</b>	<b>Late-Int</b>	<b>M</b>	<b>young</b>	-	-	-	-	-
Cam8 TA1	Late	F	mid	3.3	43.3	-12.1	15.1	24.0
Cam8 TA2	Late	M	mid-old	3.4	43.5	-11.9	15.0	22.7
Cam8 TA4	Late	M	old	3.3	42.7	-11.8	15.3	22.9
Cam8 TUW1	Late	M	old	3.3	41.2	-11.6	14.7	21.0
Cam8 T3	Late	F?	mid	3.2	40.7	-12.2	14.6	25.2
Cam8 T4 cuad F4	Late	M	young-mid	3.4	43.6	-11.9	15.0	25.1
Cam8 T6	Late	F	young-mid	3.4	42.2	-12.5	14.7	23.8
Cam8 T9	Late	f?	young	3.4	39.7	-13.1	13.7	23.7
Cam8 T15	Late	F	old	3.3	40.6	-12.5	14.4	20.5
Cam8 T19	Late	F?	mid-old	3.3	41.3	-12.1	14.5	23.4
Cam9 T2	Late	F?	young?	3.3	41.5	-11.0	14.6	24.2
Cam9 T8	Late	M	mid	3.3	44.1	-10.9	15.4	24.2
Cam9 T12	Late	F	mid	3.4	43.2	-11.1	15.0	23.0
Cam9 T13	Late	M	old?	3.4	43.7	-10.7	15.1	23.5
Cam9 T14	Late	M	young	3.7	43.0	-11.7	13.6	24.9
Cam9 T15	Late	U	U	3.5	44.2	-10.5	14.7	24.8
Cam9 T16	Late	F?	mid	3.3	42.4	-11.7	14.9	24.3

Cam9 T19	Late	F	young	3.3	43.2	-11.0	15.3	23.8
Cam9 T23	Late	U	young	3.4	43.5	-10.3	15.1	24.6
Cam9 T32c2	Late	M	young?	3.5	43.4	-11.3	14.6	24.8
Cam9 T33	Late	M	mid	3.4	43.4	-10.4	14.9	24.6
Cam9 T54c2	Late	F?	young?	3.3	42.8	-11.8	15.0	24.0
Cam9 T57	Late	U	U	3.4	43.3	-9.9	14.7	24.6
Cam9 T59	Late	F	U	3.2	42.0	-12.1	15.4	24.8
Cam9 T61	Late	F?	mid	3.4	41.3	-10.5	14.3	22.0

**Supplementary table 1:** Giving full isotopic results including collagen quality indicators for all analysed individuals. Skeletal sex information was undertaken using Buikstra & Ubelaker [1]. F = female, M = male, U = unknown. Age categories are derived from the scoring of the pubic symphysis [2] and auricular surface [3], with epiphyseal fusion taken into account in the case of young adults (Buikstra and Ubelaker, 1994). All isotopic measurements were taken in duplicate, data given here is the mean value, the difference between all repeat measurements was used to calculate the technical error of measurement on isotopic ratios (TEM  $\delta^{13}\text{C} = 0.2\text{‰}$ ;  $\delta^{15}\text{N} = 0.14\text{‰}$ ).

Individuals highlighted in bold have failed collagen quality checks/ did not give a collagen yield (indicated by -) and are therefore not included in-text. Collagen was considered to be of good quality if the: C/N ratio = 2.9 - 3.6 and 35-50% carbon and 11-16% nitrogen, as per Durham University Archaeology lab standards (based on [4])

#### References:

1. Buikstra JE, Ubelaker DH (1994) Standards for data collection from human skeletal remains.
2. Brooks S, Suchey JM (1990) Skeletal age determination based on the os pubis: a comparison of the Acsádi-Nemeskéri and Suchey-Brooks methods. Human evolution 5: 227-238.
3. Lovejoy CO, Meindl RS, Pryzbeck TR, Mensforth RP (1985) Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. American Journal of Physical Anthropology 68: 15-28.

4. Ambrose SH (1990) Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science* 17: 431-451.

Phase	C <sub>3</sub> input				C <sub>4</sub> input				Terrestrial meat input				Marine input			
	+1.5 both C & N	-1.5 both C & N	-1.5 C, +1.5 N	+1.5 C, -1.5 N	+1.5 both C & N	-1.5 both C & N	-1.5 C, +1.5 N	+1.5 C, -1.5 N	+1.5 both C & N	-1.5 both C & N	-1.5 C, +1.5 N	+1.5 C, -1.5 N	+1.5 both C & N	-1.5 both C & N	-1.5 C, +1.5 N	+1.5 C, -1.5 N
Archaic	34 ± 13	33 ± 10	32 ± 11	34 ± 11	10 ± 6	8 ± 5	12 ± 6	8 ± 5	21 ± 9	13 ± 6	18 ± 7	15 ± 7	35 ± 7	46 ± 6	38 ± 7	43 ± 6
Formative	32 ± 22	28 ± 19	31 ± 20	29 ± 20	20 ± 14	29 ± 17	32 ± 17	19 ± 13	36 ± 20	24 ± 16	25 ± 16	34 ± 19	12 ± 9	19 ± 11	12 ± 9	18 ± 10
Middle Horizon	27 ± 17	13 ± 10	15 ± 11	26 ± 17	35 ± 13	57 ± 12	60 ± 11	32 ± 14	18 ± 12	9 ± 6	9 ± 7	17 ± 11	20 ± 13	21 ± 12	16 ± 11	25 ± 13
Late-Int	30 ± 20	21 ± 16	22 ± 16	29 ± 19	30 ± 16	44 ± 17	48 ± 17	26 ± 15	25 ± 16	14 ± 11	16 ± 11	23 ± 15	15 ± 11	21 ± 12	14 ± 12	22 ± 12
Late	23 ± 15	10 ± 8	11 ± 9	23 ± 14	30 ± 12	46 ± 11	55 ± 10	25 ± 12	16 ± 10	5 ± 4	7 ± 5	11 ± 8	31 ± 9	39 ± 8	27 ± 8	41 ± 7

**Supplementary Table 2:** Reconstructed % contributions to diet by phase in alternative models where food source inputs values have been changed by ±1.5‰



Phase	C <sub>3</sub> input			C <sub>4</sub> input			Terrestrial meat input			Marine input		
	No priors	+1 offset	-1 offset	No priors	+1 offset	-1 offset	No priors	+1 offset	-1 offset	No priors	+1 offset	-1 offset
Archaic	17 ± 13	34 ± 12	34 ± 10	28 ± 14	10 ± 6	8 ± 5	11 ± 8	19 ± 8	14 ± 7	44 ± 13	37 ± 7	44 ± 6
Formative	30 ± 21	32 ± 21	29 ± 19	24 ± 16	21 ± 14	27 ± 16	29 ± 18	34 ± 19	26 ± 17	16 ± 12	13 ± 9	18 ± 11
Middle Horizon	19 ± 14	25 ± 16	15 ± 11	43 ± 16	42 ± 12	53 ± 12	12 ± 9	17 ± 11	10 ± 7	26 ± 18	20 ± 13	22 ± 13
Late-Intermediate	25 ± 18	29 ± 19	22 ± 16	35 ± 17	32 ± 16	42 ± 17	19 ± 13	23 ± 15	16 ± 12	21 ± 15	16 ± 11	20 ± 11
Late	15 ± 11	21 ± 14	11 ± 9	35 ± 14	33 ± 12	45 ± 11	9 ± 7	13 ± 9	6 ± 5	41 ± 13	33 ± 9	38 ± 8

**Supplementary Table 3:** Reconstructed % inputs to diet when a) prior assumptions regarding protein carbon contribution are removed and b) diet-collagen offsets are changed by 1‰.

Phase	C <sub>3</sub> input	C <sub>4</sub> input	Terrestrial meat input	Marine input
Archaic	n/a	n/a	n/a	n/a
Formative	n/a	n/a	n/a	n/a
Middle Horizon	21 ± 14	47 ± 13	13 ± 9	19 ± 13
Late-Intermediate	27 ± 18	37 ± 17	20 ± 13	16 ± 12
Late	17 ± 12	42 ± 13	10 ± 7	31 ± 10

**Supplementary Table 4:** Reconstructed % contributions to diet when guano fertilized C<sub>4</sub> plants are considered a possibility. Note that this model is applied only to Middle Period onwards as archaeological evidence for fertilization only appears from the Middle Period.