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Modeling diet in times of change: The case of Quitor, San Pedro de Atacama, Chile

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ABSTRACT

The transition from the Middle to Late Intermediate Period in the south-central Andes saw major changes in the lifeways of peoples across northern Chile; as far-flung networks of exchange and interaction broke down, social stressors and social conflict increased. In the present work, we present isotopic data from a sample ($n = 58$) of humans drawn from several cemeteries of the Quitor *ayllu*, in the San Pedro de Atacama oases, and we use Bayesian mixture modeling to explore the effects of these broad social, economic, and political changes on synchronic and diachronic patterns of dietary variation. A series of hypotheses dealing with both temporal changes in diet and differences between the typical diets of females and males are tested. Ultimately, our research suggests that the disarticulation of the large interregional exchange networks of the south-central Andes at the end of the Middle Period significantly impacted the diets and lifestyle of local populations. This work also shows how the use of linear mixture modeling facilitates a more nuanced interpretation of dietary composition than visual inspection or regression analysis of isotopic data.

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1. Introduction

The San Pedro de Atacama oases are found at the confluence of the San Pedro and Vilama rivers in the hyperarid Atacama Desert of northern Chile. These oases are the site of long-standing human occupation, particularly after ~3000 BP, when permanent settlers occupied the fertile oases (Llagostera, 2004; Núñez, 1991). Between the Middle (500–1000 CE) and Late Intermediate Periods (1000–1450 CE), local populations experienced a substantive shift in regional lifeways resulting from decreased interregional interaction and environmental decline. Here we explore the impacts of these changes on diet in a sample of individuals from five cemeteries in the Quitor *ayllu*, in the northern portion of the San Pedro oases (Fig. 1).

The Middle Period (500–1000 CE) is typically characterized as a time of increased intra- and inter-regional interaction and mobility for the agro-pastoral societies of the Atacameño oases. At this time, there were stable permanent settlements in most of the available fertile areas where the local populace practiced camelid pastoralism and small-scale agriculture (Llagostera and Costa, 1999; Núñez, 2007). These activities are associated with the evidence for the production of surplus in the oases, which is bolstered by incipient craft specialization, the growth of agriculture, and individuals who focused their energies on trade and exchange networks (Llagostera and Costa, 1999; Núñez, 1991; Pimentel et al., 2007). The growing prominence and affluence of the oases in the Middle Period is reflected in notable increases in the quantity and quality of grave goods, and a substantial network of interregional interaction (Berenguer and Dauelsberg, 1989; Llagostera and Costa, 1999; Rivera, 2008). The growth of far-flung networks of exchange is evident in the local archaeological record. Objects are found in San Pedro that originate in the Bolivian lowlands and *altiplano*, the Pacific coast, and northwestern Argentina; reciprocally, Atacameño pottery from the period is also found in these areas (Berenguer, 2004; Llagostera, 1996; Stovel, 2005; Torres and Conklin, 1995; Uribe, 2002).

The subsequent Late Intermediate Period (1000–1450 CE) is generally understood to have witnessed a breakdown of these larger networks. Archaeological evidence suggests that formerly disparate populations consolidated into outlying oases as well as river valleys and canyons, perhaps seeking defensive positioning and safety, or more strategic control of local resources (Núñez, 1991). This settlement pattern change indicates substantial population aggregations, as evidenced by the construction of fortified sites, most notably the Pukará de Quitor (Llagostera and Costa, 1999; Mostny, 1949; Muñoz, 1984; Schiappacasse et al., 1989). The reasons for this change are still debated, but in large part they seem to result from the broader collapse of the interregional networks that characterized the Middle Period, the retreat of Tiwanaku (Janusek, 2004; Llagostera, 1996; Núñez, 2007), and increasing aridity (Erickson, 1999; Llagostera, 2004; Ortloff and Kolata,

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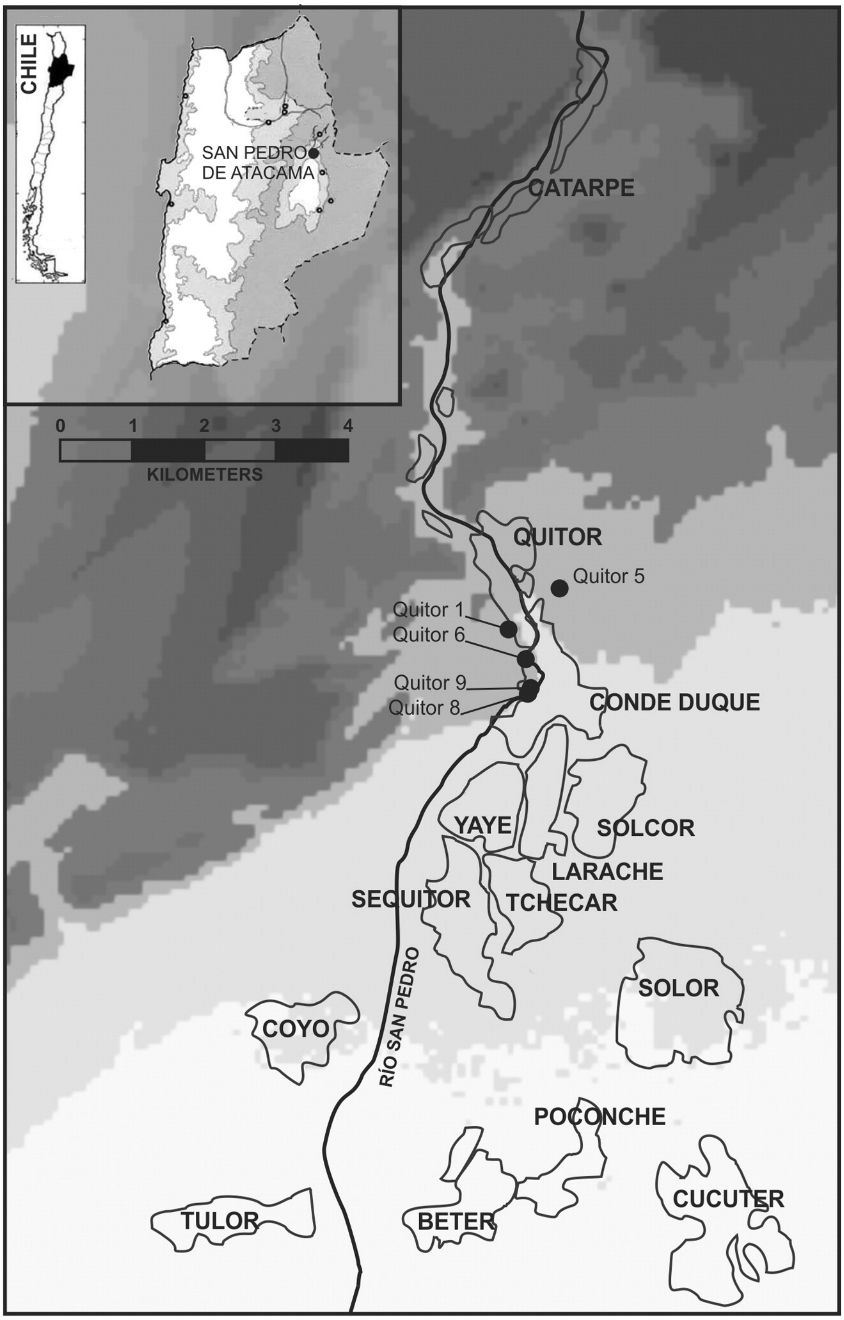

Fig. 1. Map of the San Pedro de Atacama oases, with locations mentioned in text noted.

1993), which likely caused resource stress in the already environmentally marginal societies of the highland Atacama Desert (Berenguer, 2004: 505). Independent of cause, the Late Intermediate Period saw a shift of power towards local leadership and an amplification of social conflict, suggesting increased levels of social stress (e.g., Núñez, 1991; Torres-Rouff and Costa, 2006).

These broader environmental, economic, and social patterns are associated with important changes in aspects of local lifestyle, which, we argue, could be reflected in coeval changes in local diet. It has been thought that the trade networks of the Middle Period, together with a generally higher level of prosperity, could have brought exotic foodstuffs to the residents of the San Pedro oases, or more likely increased access to expensive foodstuff (e.g. meat; Hubbe et al., 2012). However, the Middle Period also saw increasing evidence of social inequality which likely affected access to these resources based on one's social status and/or sex (e.g. Costa and Llagostera, 2004; Llagostera, 1996; Núñez, 2007; Torres-Rouff, 2011). Given external stressors and the inward-shift of the Late Intermediate Period populations, it has been argued that the local populations at this time emphasized or were restricted to local resources and the intensification of production of certain domesticates, for example, maize (Llagostera, 2004; Llagostera and Costa, 1999; Núñez, 2007). We seek to understand the dietary embodiment of these broad environmental, economic, and social processes and changes in the present work.

2. Research question and hypotheses

Evidence for a dietary shift between the Middle and Late Intermediate Periods has been compiled, for the most part, through analysis of dental pathology (e.g., Costa et al., 2004; Hubbe et al., 2012), although see Santana-Sagredo et al. (2015) for an example of an isotopic approach to these questions. The multifactorial nature of dental markers makes interpretations of dietary shifts prone to generalizations that cannot be tested against broader changes in the archaeological record. Here we use stable isotope analysis, and the application of linear mixing models, to quantify dietary makeup as to test hypotheses and predictions made in studies based exclusively on osteological and dental markers. Our goal is to complement current archaeological and bioarchaeological discussions about the nature of the Middle to Late Intermediate Period transition in the Atacameño oases, and provide a more refined interpretation of the consequences that these social and environmental changes had on local lifestyle.

To this end, we present here a detailed examination of how the substantive shifts in regional lifeways associated with the transition to the Late Intermediate Period manifested in the diets of individuals from the *ayllu* of Quitor, one of the northernmost districts of San Pedro de Atacama (Fig. 1). The Quitor area shows an intense occupation during both periods of interest, as attested to by the dense and expansive cemeteries with material culture of both periods. The existence of these cemeteries permits comparative analysis of large skeletal samples between and within periods. Moreover, some of the cemeteries of the present study have been included in past bioarchaeological studies, particularly the Late Intermediate Period site of Quitor 6 Tardío, providing us with a broad array of available information about the local inhabitants' lifestyle and biological affinities (Costa, 1988; Costa et al., 2004; Da-Gloria et al., 2011; Knudson et al., 2015; Neves and Costa, 1998; Torres-Rouff et al., 2015). In light of our previous work on dental markers and their association with diet in Atacameño populations (Hubbe et al., 2012), we test a series of hypotheses in terms of local synchronic and diachronic dietary variation and offer nuanced interpretations in light of the in-depth investigations conducted in the area. We acknowledge from the outset that this work is provisional and that the expansion of sample size or refinement of model parameters could impact the conclusions reached here.

2.1. Temporal difference

Given the relative abundance and cultural diversity of the Middle Period in contrast to the social and environmental constraints that arose during the Late Intermediate Period, we first hypothesize greater diversity in isotopic composition, and thus dietary composition, in the Middle Period. Second, as previous studies (Costa et al., 2004; Hubbe et al., 2012; Neves and Costa, 1998) have suggested dietary causes as the explanation for the decrease in caries prevalence and higher average stature during the Middle Period, when compared to the Late Intermediate Period, we test here whether this transition between periods brought about 1) decreased access to, and consumption of, meat, and 2) a shift towards greater consumption of C_4 carbohydrates (i.e., maize).

2.2. Sex within periods

Previous examination of dental health in several Atacama oasis cemeteries revealed differences between the sexes in the prevalence of caries (Hubbe et al., 2012) suggesting that females within each period had access to a) less meat, and b) different dietary carbohydrates than their male contemporaries. These differences could be a consequence of gendered difference in access to certain food classes, for example maize *chicha,* or perhaps reflect different lifestyle and labor patterns for the sexes (Cuellar, 2013; Goldstein, 2005: 254; Hastorf, 1991). It should be noted that the precise relationship between food class intake and caries is far from straightforward and could be affected by the differential cariogenic potential of varied foodstuffs (maize versus other plant foods) and the preparation of those foods (liquid corn *chicha* versus solid corn). Regardless, we suggest that these gender differences would be larger in the Middle Period than in the Late Intermediate Period, reflecting greater differences in social standing/inequality at the time.

2.3. Sex between periods

Finally, it is expected that, over time, female diet would remain more consistent, whereas male diet is expected to shift more heavily in the Late Intermediate Period towards a) less meat, and b) more maize than was consumed in the Middle Period. This expectation is also based on previous studies (Hubbe et al., 2012; Costa et al., 2004) suggesting that gender inequalities were more pronounced during the Middle Period, where the abundance of resources would allow for differential access to certain foods (see above). During the Late Intermediate Period, with the reduced availability of resources, males would be forced to “fall back” to the kinds of dietary combination previously consumed by women. Moreover, the reduction of the interregional exchange networks that characterized the Middle Period, and the concomitant reduction in the movement of llama herds and the men that presumably travel with them, would likely contribute to greater male and female diet similarities during the Late Intermediate Period.

As noted earlier, this series of hypotheses is based on previous attempts to reconcile osteological/dental evidence with archaeological evidence of cultural and environmental change in the region. They are, however, likely simplistic given the aforementioned multifactorial quality of dental pathology. Therefore, the ad-hoc nature of the explanations may be strongly biased by a binary view of diet in the past, with overemphasis on the dichotomy of meat and vegetables (e.g. Costa et al., 2004; Hubbe et al., 2012; Neves and Costa, 1998). The combination of biochemical analyses with the strong predictive modeling techniques employed here allows for a more direct and less biased test of the possible diet composition changes observed in the past. The results are potentially much stronger because they derive from a model-bound approach instead of ad-hoc model-free discussions of data patterns.

3. Isotopic background

Stable isotope analysis is currently the principal archaeological means for reconstructing the diet of ancient human populations. Forty years of successful application have established a corpus of well-tested methods that enable the accurate reconstruction of broad aspects of human paleodiet (Ambrose, 1993; Lee-Thorp, 2008). In brief, the isotopic makeup (expressed using the δ notation, the ratio of the heavier to lighter isotope as compared to an international standard) of consumer bone collagen and hydroxyapatite, having been corrected for fractionation, is compared with the isotopic values of the range of locally available foodstuffs. Comparison of consumer and foodweb values allows for determination of the relative importance of different foodstuffs to individual consumer diet, and more recently developed linear mixing models permit the probabilistic and uncertainty-integrated quantification of food group contributions (Fernandes et al., 2014; Stock and Semmens, 2013). Assuming sufficient preservation of target biomolecules and accurate knowledge of local foodwebs and fractionation values, broad aspects of individual paleodiet can be reconstructed with a high degree of accuracy.

To strengthen the interpretation of isotopic data, the past several decades have witnessed the development of linear mixture modeling tools that enable a greater degree of quantification of food class contribution from isotopic data, thereby greatly improving the explanatory power of bioarchaeological reconstructions of paleodiet (e.g. Fernandes et al., 2015). These approaches produce nondeterministic solutions for scenarios where potential food sources outnumber isotope proxies (making deterministic solutions impossible), and in some cases begin to confront issues of uncertainty in such reconstruction. These tools, “offer a powerful means to interpret data because they can incorporate prior information, integrate across sources of uncertainty and explicitly compare the strength of support for competing models or parameter values” (Moore and Semmens, 2008: 471). Crucially, these approaches are model-bound and therefore infer the probability of possible alternatives fitting the observed data following Bayesian principles. This sets them apart from previous work (e.g., Fernandes et al., 2012; Froehle et al., 2012), which fit possible explanations of diet only after patterns in the data are defined.

4. Materials

In the present work, we consider the remains of fifty-eight individuals from five of the Quitor cemeteries, covering the Middle Period and Late Intermediate Period occupation of the area (Table 1). The Quitor oasis sits at the north end of the cluster of oases that make up San Pedro de Atacama, with direct access to the waters flowing in the San Pedro River (Fig. 1). Not surprisingly, it has been home to a long-standing occupation up to and including serving as a site of local resistance to the Inka and Spanish conquests (Mostny, 1949; Muñoz, 1984).

During the course of his long career, Father Gustavo Le Paige, a long-serving local Jesuit priest, excavated nearly a dozen cemeteries in the Quitor oases, resulting in the recovery of hundreds of individuals, whose crania were retained in his namesake museum (Hubbe et al., 2011; Le Paige, 1964). In the mid 1980s, a scientific excavation was conducted in the late sector of the Quitor 6 cemetery (Quitor 6 Tardío) by Dr. Agustín Llagostera and the staff of the *Instituto de Investigaciones Arqueológicas* of the Universidad Católica del Norte, which resulted in the careful documentation of over 60 individuals and their graves. Taken together, the individuals recovered from the Quitor cemeteries span the length of the occupation of the oases, and provide particularly robust samples from the Middle and Late Intermediate Periods.

In addition to the newly analyzed individuals presented here, Santana-Sagredo et al. (2015) recently published the results of isotopic analysis of thirteen Late Intermediate Period individuals from the Quitor 6 Tardío cemetery. The relationship between the present results and this work is also considered in our discussion, below.

5. Methods

Age and sex of individual skeletons were estimated following standard protocols (Buikstra and Ubelaker, 1994; Buzon et al., 2005). Sampling for isotopic analysis took place in the Museo Gustavo Le Paige in San Pedro de Atacama, Chile. Samples of dense cortical bone (1–2 g target weight) were removed using a diamond cut-off wheel mounted on a handheld rotary tool. During sampling, the rotational speed of the tool was kept as slow as possible to limit any possible denaturation of proteins and a decrease in collagen yield. Following extraction, samples were bagged in pre-labeled sterile sample bags. Cut-off wheels were cleaned between uses with dilute bleach and distilled water and subsequently air-dried.

Extractions of target biomolecules (collagen and hydroxyapatite) were performed in the Archaeological Stable Isotope Lab at the University of Miami. Collagen extraction followed a modified version of that established by Longin (1971) and previously detailed elsewhere (Pestle, 2010). Weighed 0.5 g aliquots of coarsely ground (0.5–1.0 mm) cortical bone were placed in 50 ml centrifuge tubes, to which was added 30 ml of 0.2 M HCl. The tubes were capped and placed in a constantly spinning rotator for 24 h, at which time the degree of demineralization was assessed, with neutral buoyancy of particles taken as evidence of demineralization. Samples requiring another 24 h to demineralize had their acid refreshed at this time. After demineralization, samples were rinsed to neutral and treated with 30 ml of 0.0625 M NaOH for a period of 20 h. After this removal of humics, samples were again rinsed to neutral, and then gelatinized for 24 h at 90 °C in 10^{-3} M HCl. The resulting gelatin was then filtered using 40 μm sterile single-use Millipore Steriflip ® vacuum filters, allowed to condense at 85 °C, frozen, and then freeze-dried. Collagen yield data were collected after extraction and freeze-drying as a first measure of sample preservation.

Table 1
Composition of study sample, by cemetery, period, and sex.

Cemetery	*n*	*n* well-preserved	Female	Male	Indeterminate
Middle Period					
Quitor 5	19	17	5	6	6
Quitor 8	12	3	2	0	1
Late Intermediate Period					
Quitor 1	6	5	0	0	5
Quitor 6 T	14	12	8	1	3
Quitor 9	7	4	1	3	0

Extraction and purification of bone hydroxyapatite followed the protocol of Lee-Thorp (1989) and Krueger (1991), with minor modifications (Pestle, 2010). Briefly, weighed 0.1 g aliquots of a fine-ground (0.125–0.25 mm) fraction of cortical bone were placed in 50 ml centrifuge tubes. This material was first oxidized for 48 h using 30 ml of a 50% solution of commercial bleach (sodium hypochlorite), with a reagent change after 24 h. After all sample organics were oxidized, samples were rinsed to neutral and labile carbonates were removed using 30 ml of 0.1 M acetic acid. This acid treatment lasted four hours, with a 5-min vacuum treatment at the two-hour mark. Following this treatment, samples were rinsed to neutral, frozen, and freeze-dried. Hydroxyapatite yield was recorded subsequent to extraction and lyophilization.

Isotopic analysis of both collagen and hydroxyapatite was performed in the Marine Geology and Geophysics' Stable Isotope Laboratory at the University of Miami's Rosenstiel School of Marine and Atmospheric Science. Collagen samples were analyzed using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (IRMS). This process produces data on both sample elemental composition (carbon and nitrogen yield, from which atomic C:N can be computed) as well as the isotopic measures of $\delta^{13}C_{co}$ and $\delta^{15}N_{co}$. Hydroxyapatite samples were analyzed using a Kiel-IV Carbonate Device coupled to a Thermo-Finnigan DeltaPlus IRMS, producing $\delta^{13}C_{ap}$ values for the analyzed samples. Typical precision of in-house organic standards (acetanilide and glycine) was ±0.07‰ for $\delta^{13}C$ and ±0.11‰ for $\delta^{15}N$ whereas, for carbonates (using an in-house carbonate standard calibrated to NBS-19), precision was better than ±0.07‰ for $\delta^{13}C$.

Statistical comparison of isotopic values and simulated foodstuff contributions were made using Student's *t*-tests except in those cases where reductions in sample size compelled the use of nonparametric statistics for group comparison (Mann-Whitney U).

Average isotope values (with errors, see below), by period and sex, were analyzed using the Bayesian multi-source mixture modeling software FRUITS (Food Reconstruction Using Isotopic Transferred Signals, Fernandes et al., 2014). This analysis allows for probabilistic and uncertainty-integrated quantification of dietary inputs. FRUITS was chosen because of its capability for incorporating food macronutrient, elemental, and isotopic composition as well as source and consumer uncertainty in its calculations.

For the purposes of this analysis, we determined the consumer-foodstuff offset in $\delta^{13}C_{co}$ using the two-term linear regression method (with ±1.9‰ error) as described in Pestle et al. (2015a). The offset (fractionation) factor in $\delta^{13}C_{ap}$ was stipulated as 10.1 ± 0.4‰, as specified by Fernandes et al. (2012). Finally, for $\delta^{15}N$, we employed a trophic fractionation value of 3.6 ± 1.2‰, as recommended by several experimental studies of omnivorous animals (Ambrose, 2000; DeNiro and Epstein, 1981; Hare et al., 1991; Howland et al., 2003; Sponheimer et al., 2003; Warinner and Tuross, 2009).

Foodweb isotope values comprised the edible portions of over 119 southern Andean plant and animal samples, including previously published data (DeNiro and Hastorf, 1985; Miller et al., 2010; Schoeninger and DeNiro, 1984; Tieszen and Chapman, 1992) and data generated through our ongoing work in the region (Pestle et al., 2015b). While we cannot guarantee that the foodweb (Table 2) represents all foodstuffs available to ancient peoples of the region, all of the items in the foodweb represent foodstuffs that were *potentially* available to the populations under study. Furthermore, the low isotopic variance of each category would seems to indicate that the addition (or subtraction) of

Table 2
Food group isotope, macronutrient, and elemental concentration values used in FRUITS simulations.

		Macronutrient concentration (%)				%C				Tissue δ^{13}C (‰)					Tissue δ^{15}N (‰)	
Food grouping	Group *n*	Protein	Fat	Carbohydrates	Energy	Protein	Fat	Carbohydrates	Energy	Bulk	Protein	Fat	Carbohydrates	Energy	Bulk	Protein
Terrestrial mammals	30	83 ± 12	16 ± 12	1 ± 3	17 ± 12	43 ± 12.7	12 ± 12.1	0 ± 4.2	13 ± 12.7	−18.3 ± 3.9	−20.3 ± 3.9	−25.3 ± 3.9	−18.8 ± 3.9	−25.1 ± 3.9	7 ± 1.7	9 ± 1.7
C_3 plants	59	11 ± 5	5 ± 4	84 ± 7	89 ± 5	5 ± 6.9*	4 ± 6.7	37 ± 8.5	41 ± 6.9	−23.9 ± 1.4	−25.9 ± 1.4	−29.9 ± 1.4	−24.4 ± 1.4	−24.9 ± 1.4	6.2 ± 3.5	6.2 ± 3.5
C_4 plants	12	11 ± 5	5 ± 4	84 ± 7	89 ± 5	5 ± 6.9*	4 ± 6.7	37 ± 8.5	41 ± 6.9	−10.2 ± 1.1	−12.2 ± 1.1	−16.2 ± 1.1	−10.7 ± 1.1	−11.2 ± 1.1	8.2 ± 3.6	8.2 ± 3.6
Legumes	18	28 ± 2	2 ± 1	71 ± 3	72 ± 2	13 ± 5.6*	1 ± 5.3	31 ± 5.8	33 ± 5.6	−23.4 ± 1.4	−25.4 ± 1.4	−29.4 ± 1.4	−23.9 ± 1.4	−24.1 ± 1.4	1.9 ± 1.6	1.9 ± 1.6

* Assumes 87.4% digestibility of plant protein as compared to animal protein.

a handful of individual taxa/specimens would have relatively little effect on the central tendency or dispersion of the food group isotope values. The only exception to this pattern of low variance is the terrestrial mammal group, which shows somewhat higher isotopic dispersion. In this case, however, we are comfortable with the use of a relatively broad category, because there is not enough information in the archaeological record to quantify the relative proportion of different kinds of animals (e.g. wild versus foddered) in local diet. As such, the foodweb employed represents a conservative approach to dietary reconstruction.

Any modern data included in this reference sample had δ^{13}C values corrected by + 1.5‰ to account for the fossil fuel burning effect (Keeling et al., 1979). Macronutrient composition of each food group was determined by reference to a range of comparable foodstuffs in the USDA National Nutrient Database for Standard Reference (USDA, 2013). Elemental composition (particularly %C) of each foodstuff/macronutrient group was based on formulae provided in Morrison et al. (2000). Isotopic offsets between measured bulk food isotope values and the isotopic values of specific dietary macronutrients were derived from Tiesezen (1981). Digestibility was determined following Hopkins (1981). Final food group isotope, macronutrient, and elemental concentration values used in the FRUITS simulations are all presented in Table 2. Marine foodstuffs, common in Atacama coastal populations, were not included as a potential source given the lack of archaeological evidence for their presence in the San Pedro oases. Consumption of protein was limited to <45% protein as energy (using the FRUITS a priori data option), reflecting the upper limit of possible human protein intake (World Health Organization, 2007). All FRUITS simulations were performed using 10,000 iterations and, when comparing average values of different periods or other sample subgroups, standard deviations of the average values were included as an additional source of uncertainty. In this way, we account for the variation within each subgrouping.

Two separate sets of simulations were performed for each subgrouping. The first, Simulation A, included three possible food sources (terrestrial animal meat, C_3 plants, C_4 plants), reflecting the food categories that have been considered in most bioarchaeological studies (Costa et al., 2004; Hubbe et al., 2012). The second, Simulation B, added legumes, alongside the more common terrestrial animals and local protein-poor plants, as an additional food source due to their presence in regional archaeological assemblages, and the potential ways in which their high protein, low δ^{15}N composition might influence paleodietary interpretation. While there is archaeological evidence for the presence of various legumes in the region surrounding San Pedro de Atacama (Arriaza et al., 2015; Latcham, 1938; Núñez et al., 2009; Thomas et al., 1995), we have no clear evidence for their inclusion in local diets. The lack of local archaeological visibility could result, however, from the paucity of paleobotanical studies performed in the area to date. As such, legumes are included here in Simulation B to test what effect their inclusion may have on our reconstruction of local diet, despite the fact that they have been mostly ignored by the bioarchaeology literature so far. Statistical comparison of isotopic values and simulated foodstuff contributions were made using Student's *t*-tests and ANOVA (with Tukey HSD Post-hoc testing). Due to the possibility of overfitting with the large sample sizes in the simulations ($n = 10.000$), we assume an alpha of 0.001 for all comparisons of modeled foodstuff contributions.

6. Sample preservation

The quality of sample preservation for all fifty-eight samples was assessed using chemical (collagen yield) and elemental (carbon and nitrogen yield, atomic C:N ratio) data, all of which are routinely generated in the course of sample extraction and elemental analysis. Only those samples meeting widely accepted standards (collagen yield >0.5 wt%, carbon and nitrogen yields of >4.5 wt% and 0.9 wt%, respectively, and atomic C:N ratios between 2.9 and 3.6) were included when considering aspects of paleodiet (Ambrose, 1990; Pestle and Colvard, 2012). Details of the varying state of preservation in the five cemeteries are presented in Table 3.

Overall, 71% (41/58) of the analyzed samples possessed sufficient unaltered collagen for isotopic study. Preservation at Quitor 8 was the worst of the studied cemeteries, with an average collagen yield of only 2.0 ± 1.0 wt%. Of the twelve analyzed samples from Quitor 8, only three (25%) had elemental characteristics (carbon and nitrogen elemental yields, and atomic C:N ratios) consistent with well-preserved collagen. In stark contrast, seventeen of the nineteen samples (89%) from Quitor 5 had sufficient well-preserved collagen for further analysis, with an average collagen yield of 12.5 ± 7.7 wt%. The other three cemeteries had success rates (defined as sufficient well preserved collagen) of 57% (Quitor 9), 83% (Quitor 1), and 86% (Quitor 6 T). Isotopic data for all samples are presented in Table 3 and Fig. 2.

There does not appear to be a clear temporal trend in collagen preservation, as the best and worst preserved cases (Quitor 8 and 5) are roughly contemporary Middle Period cemeteries, and the remaining three belong to the Late Intermediate Period, despite having collagen preserved in quite different proportions (57%–86%). Rather than time, the prevailing groundwater conditions would seem to be the dominant factor determining bone preservation over archaeological timescales in the San Pedro oases. As Le Paige (1964:64) notes, Quitor 8 is the most proximate to the course of the San Pedro River (see Fig. 1), and bones buried there would have been subject to periodic inundation over the past millennium.

Table 3
Chemical, elemental, and isotopic data for Quitor individuals.

Site	Number	Sex	Lab number	Collagen yield (wt%)	Apatite yield (wt%)	wt% C	wt% N	Atomic C:N	$\delta^{13}C_{co}$ (‰)	$\delta^{15}N_{co}$ (‰)	$\delta^{13}C_{ap}$ (‰)	$\Delta^{13}C_{ap\text{-}co}$ (‰)
Quitor 1	3486	I	I42	16.5	48.7	43.3	15.5	3.3	−12.2	11.7	−7.4	4.7
	3454	I	I43	14.9	50.7	34.1	12.2	3.3	−13.2	11.0	−7.8	5.5
	3487	I	I44	6.3	65.5	22.3	7.6	3.4	−15.2	13.0	−9.3	5.8
	3443	I	I45	7.9	59.4	33.1	12.7	3.0	−13.4	11.1	−7.1	6.3
	3455	I	I46	1.8	55.8	10.5	2.9	4.3	−12.8	12.7	−8.0	4.8
	3493	I	I47	22.8	43.6	38.2	13.9	3.2	−14.0	9.5	−7.4	6.6
Quitor 5	1916	I	I20	13.1	48.2	32.7	11.9	3.2	−14.7	9.5	−9.2	5.5
	2245	M	I21	18.9	44.1	38.1	13.6	3.3	−11.5	10.2	−6.3	5.2
	3066	F	I22	6.3	63.0	30.0	10.7	3.3	−16.6	9.3	−12.8	3.8
	2179	M	I23	2.9	64.5	17.9	6.3	3.3	−10.9	10.8	−5.3	5.6
	2109	I	I24	18.4	45.2	39.3	14.0	3.3	−14.9	11.0	−11.1	3.8
	2100	M	I25	15.9	47.1	40.5	14.8	3.2	−12.8	10.7	−7.6	5.2
	2055	I	I26	24.1	30.4	42.2	15.2	3.2	−16.4	9.5	−10.2	6.2
	1998	I	I27	2.2	67.3	0.3	0.1	4.8	−19.0	5.7	−13.0	6.0
	2026	M	I28	21.3	44.3	40.4	14.5	3.2	−15.4	9.1	−10.8	4.6
	1942	I	I29	19.1	49.1	40.5	14.9	3.2	−17.0	9.0	−12.3	4.6
	2212	F	I30	8.6	61.3	32.7	11.7	3.3	−12.5	10.7	−7.9	4.6
	3368	F	I31	2.6	67.9	16.4	5.7	3.4	−16.5	8.6	−12.5	4.0
	3397	F	I32	11.1	57.1	–	–	–	−17.3	7.5	−12.5	4.7
	1921	M	I33	6.5	54.8	30.7	10.9	3.3	−13.0	10.5	−7.5	5.5
	2228	I	I34	4.7	62.2	19.4	6.7	3.4	−15.6	9.2	−10.2	5.3
	3370(80?)	I	I35	21.3	36.3	39.4	14.4	3.2	−15.9	9.7	−11.8	4.2
	2020	F	I36	16.2	58.5	30.4	11.0	3.2	−16.6	8.3	−12.2	4.4
	2125	M	I37	21.4	40.3	39.3	14.3	3.2	−16.1	10.0	−11.4	4.7
	3348bis	I	I38	2.8	63.0	1.2	0.1	12.8	−22.0	11.4	−9.1	12.9
Quitor 6T	T23	I	G43	0.9	60.4	10.3	2.6	4.6	−17.3	9.1	−8.5	8.8
	469/470	F	H95	19.2	33.6	39.2	14.5	3.2	−13.6	10.8	−7.8	5.9
	871	M	H96	19.3	36.8	38.0	13.6	3.3	−15.9	10.8	−10.3	5.6
	88/89	F	H97	8.3	55.2	32.2	11.6	3.2	−13.9	10.5	−8.5	5.4
	943	F	H98	3.8	60.3	25.5	8.8	3.4	−13.7	11.4	−8.0	5.7
	694	I	H99	14.2	45.3	35.6	13.1	3.2	−13.0	9.9	−7.7	5.3
	876	I	H100	21.0	36.8	38.0	13.9	3.2	−15.6	9.3	−8.8	6.8
	877	F	H101	20.4	40.4	37.2	13.6	3.2	−15.2	9.7	−10.1	5.1
	432/433	I	H102	2.4	61.9	1.3	0.4	4.1	−15.1	10.3	−6.6	8.5
	222/223	F	H103	21.2	37.4	36.1	13.3	3.2	−13.2	10.3	−7.3	5.9
	104	F	H104	22.1	42.4	39.0	14.4	3.2	−13.0	11.4	−7.8	5.2
	80/81	F	H105	4.8	65.9	28.3	9.9	3.3	−14.4	10.7	−8.7	5.7
	667	F	H-106	1.7	71.1	10.9	3.5	3.6	−13.7	10.9	−7.9	5.8
	685	I	H-107	7.0	52.1	31.7	11.7	3.2	−11.2	11.5	−6.2	5.0
Quitor 8	3184	I	H-110	1.2	69.1	3.4	0.5	7.4	−17.4	13.5	–	17.4
	3146	F	H-111	3.4	64.9	25.2	8.8	3.4	−16.4	10.3	−9.8	6.6
	3161	I	H-112	1.5	81.7	1.0	0.2	6.2	−19.2	7.3	–	19.2
	3227	I	H-113	4.3	65.3	27.1	9.4	3.3	−15.8	10.9	−11.3	4.5
	3188	I	H-114	1.7	68.6	7.4	2.2	3.9	−16.4	9.7	–	16.4
	3177	I	H-115	1.2	71.5	5.9	0.8	9.0	−16.3	13.2	–	16.3
	3166	I	H-116	1.7	77.7	1.1	0.0	31.8	−21.6	9.1	–	21.6
	3172	I	I1	1.6	27.7	0.0	0.0	–	–	–	−11.9	−11.9
	3202	F	I2	2.9	58.1	26.3	9.2	3.3	−16.5	10.5	−12.3	4.2
	3195	I	I3	1.3	54.8	0.0	0.0	–	−20.7	6.8	−11.7	9.1
	3156	I	I4	1.2	58.4	0.0	0.0	–	−19.6	10.1	−11.9	7.7
	3160	I	I5	1.5	72.9	0.4	0.1	4.5	−19.3	8.6	−11.1	8.1
Quitor 9	3250	F	H88	2.4	38.7	18.8	6.4	3.4	−13.7	12.1	−8.2	5.5
	3242	I	H89	1.1	42.8	0.0	0.0	–	−20.5	9.3	−10.9	9.6
	3237	M	H90	21.5	41.0	40.2	14.8	3.2	−11.5	12.3	−7.4	4.0
	3236	M	H91	14.3	47.2	38.9	14.2	3.2	−11.4	12.5	−6.0	5.4
	3249	M	H92	17.4	40.3	39.2	14.6	3.1	−11.7	11.2	−5.9	5.8
	3251	I	H93	2.3	54.8	9.4	2.8	3.9	−14.1	11.8	−8.4	5.7
	3239	I	H94	2.7	58.6	3.6	0.8	5.5	−13.7	14.0	−6.6	7.1

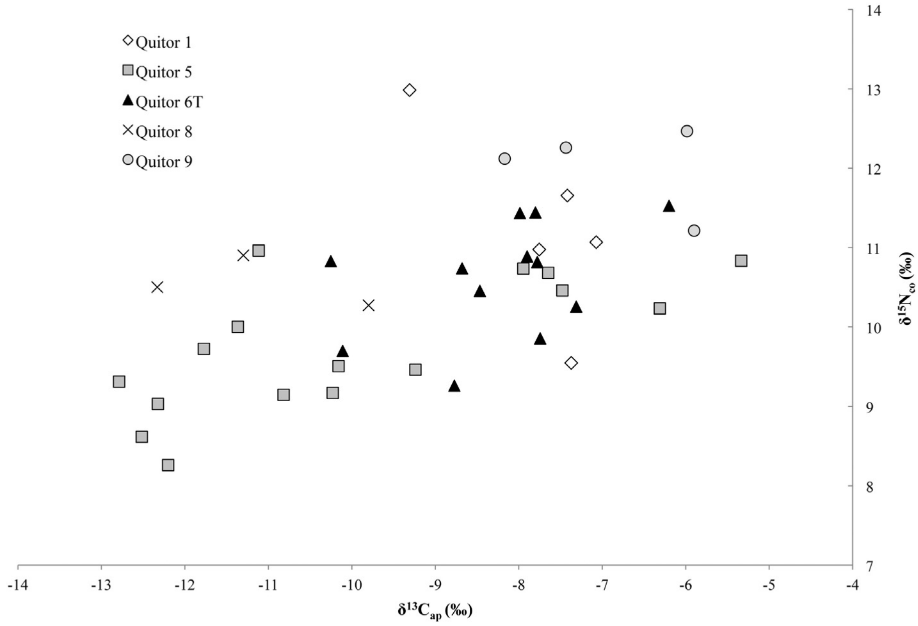

Fig. 2. $\delta^{13}C_{ap}$ and $\delta^{15}N_{co}$ values of all well-preserved Quitor bone samples.

7. Results

7.1. Temporal differences

After removing those samples that did not meet preservation standards from consideration, the remaining assemblage comprised twenty individuals from Middle Period cemeteries (Quitor 5 and 8) and twenty-one from the Late Intermediate Period (Quitor 1, 6 T, and 9). As seen in Table 4, there were significant differences (two-sample *t*-test, $p < 0.05$) between the averages of the two periods for all four of the isotopic measures, despite some degree of overlap in the ranges of each period, particularly for $\delta^{13}C_{ap}$ and $\delta^{13}C_{co}$. Late Intermediate Period individuals, on average, possessed significantly higher (more positive) $\delta^{13}C_{co}$, $\delta^{15}N_{co}$, and $\delta^{13}C_{ap}$ values than their Middle Period counterparts, as well as having larger $\Delta^{13}C_{ap\text{-}co}$ values. Importantly, our hypothesis of greater isotopic and dietary heterogeneity in the Middle Period is supported by the equal or larger standard deviations observed in each isotopic measure for that period.

FRUITS Simulation A (Fig. 3 and Table 4) found a significant 1% drop (*t*-test, $p < 0.001$) in meat consumption between the Middle Period and Late Intermediate Period, and also identified a major and significant ($p < 0.001$) shifts between the two periods in plant diet, with C_3 plant contribution falling from nearly 45% to 36%, and C_4 plant consumption increasing a commensurate amount. These results support our hypothesis that meat consumption would fall while C_4 plant consumption would rise between the two periods.

The results of Simulation B (Fig. 4 and Table 4) also identified a highly significant (two-sample *t*-test, $p < 0.001$) decrease in the consumption of C_3 plants (27% to 23%) and a commensurate significant increase in C_4 plant consumption. In terms of protein-rich foods, this modeling iteration found a significant drop ($p < 0.001$) in the eating of legumes (25% to 18%) and a small but significant increase (just over 1%) in meat consumption between the periods. Put differently, dietary change from the Middle Period to Late Intermediate Period in Quitor would appear to have consisted of the replacement of C_3 plants by C_4 plants (likely maize) and the consumption of fewer legumes and more meat/terrestrial animal products than consumed previously. Therefore, when legumes are included in the simulations, the increase in $\delta^{15}N_{co}$ observed between periods, which in Simulation A is explained by a decrease in meat consumption that is more than offset by an increase in ^{15}N-enriched C_4 plants, can instead be explained by a large decrease in legume consumption. These results only partially meet with our predictions, as this model indicates that terrestrial meat played a larger role in the typical Late Intermediate Period diet than it did in the Middle Period.

7.2. Sex within periods

Considering only those adults for whom sex could be determined with a high degree of confidence further reduced sample size (Table 4). For the Middle Period, the sample consisted of 7 females and 6 males, and for the Late Intermediate Period, 9 females and 4 males. We acknowledge that these sample sizes are small, and present the following discussions as a means of preliminarily testing, by biogeochemical means, sex differences in food access/consumption seen in osteological studies of larger local sample sizes (Hubbe et al., 2012; Costa et al., 2004), and thereby contributing, in a general sense, to the conversation about gender in the Atacama oases. The first comparisons taking sex into account were made between the sexes of each period.

Beginning with the Middle Period, there were significant differences (Mann Whitney U, $p < 0.05$) observed for both $\delta^{13}C_{co}$ and $\delta^{13}C_{ap}$. For both variables, females possessed significantly lower (more negative) values than their male counterparts. $\Delta^{13}C_{ap\text{-}co}$ and $\delta^{15}N_{co}$ did not exhibit significant differences by sex.

FRUITS Simulation A (Fig. 3 and Table 4) found that females and males of the Middle Period differed slightly, but significantly, in their terrestrial meat consumption (*t*-test, $p < 0.001$), with males having diets consisting of roughly 1% more meat. Much larger, and clearly significant differences (*t*-test, $p < 0.001$) also were identified in terms of the balance of plant consumption, with females having consumed roughly 15% more C_3 and 15% fewer C_4 plants than their male contemporaries. These results support our expectation that females of the Middle Period would have consumed less meat and fewer C_4 plants than their male contemporaries.

Results of FRUITS Simulation B (Fig. 4 and Table 4) indicated highly significant (*t*-test, $p < 0.001$) differences in the average contribution of each modeled food source between the two sexes in the Middle Period. As above, females would appear to have consumed significantly more C_3

Table 4
Isotopic data and modeled foodstuff contributions (Simulations A and B) for sample subgroups.

	n	Isotope values (‰)				Simulation A (% contribution): mean ± sd, 2.5%–95%			Simulation B (% contribution): mean ± sd, 2.5%–95%			
		$\delta^{13}C_{co}$	$\delta^{15}N_{co}$	$\delta^{13}C_{ap}$	$\Delta^{13}C_{ap\text{-}co}$	TM	C_3	C_4	TM	Legumes	C_3	C_4
Middle Period	20	−15.1 ± 1.9	9.8 ± 1.0	−10.3 ± 2.2	4.9 ± 0.8	29.8 ± 17.1 2.0–59.4	44.7 ± 17.6 10.9–79.9	25.5 ± 14.0 2.3–54.3	27.5 ± 18.3 1.6–69.9	24.9 ± 16.9 1.1–62.0	27.0 ± 18.0 1.2–64.8	20.6 ± 12.8 1.2–47.7
Females	7	−16.0 ± 1.6	9.3 ± 1.2	−11.4 ± 1.8	4.6 ± 0.9	28.2 ± 16.7 1.4–58.8	52.8 ± 17.0 17.6–83.6	19.0 ± 11.6 1.3–43.7	26.5 ± 18.3 1.5–69.8	27.7 ± 17.9 1.3–66.4	29.6 ± 19.1 1.4–70.4	16.2 ± 10.8 0.9–41.0
Males	6	−13.3 ± 2.1	10.2 ± 0.6	−8.2 ± 2.4	5.1 ± 0.4	29.7 ± 16.6 2.0–58.7	34.2 ± 16.4 4.7–68.8	36.2 ± 16.7 4.3–67.8	27.6 ± 18.8 1.4–69.5	20 ± 14.5 0.9–53.5	22.2 ± 16.3 0.9–59.1	30.1 ± 15.5 2.4–61.1
Late Intermediate Period	21	−13.5 ± 1.4	11.0 ± 1.0	−7.9 ± 1.2	5.6 ± 0.6	28.7 ± 16.8 1.5–58.5	36.2 ± 14.9 6.3–63.9	35.2 ± 13.4 7.2–60.0	29.1 ± 19.0 1.7–72.1	17.9 ± 13.0 0.7–47.6	22.9 ± 14.9 1.3–55.0	30.0 ± 13.8 3.3–55.0
Females	9	−13.8 ± 0.7	10.9 ± 0.7	−8.2 ± 0.8	5.6 ± 0.3	28.9 ± 16.5 1.9–58.5	37.9 ± 14.3 6.5–63.2	33.2 ± 12.4 6.6–55.2	28.2 ± 19.0 1.3–71.0	18.2 ± 13.4 0.7–48.9	23.8 ± 15.3 1.1–55.3	29.7 ± 12.5 3.0–51.2
Males	4	−12.6 ± 2.2	11.7 ± 0.8	−7.4 ± 2.0	5.2 ± 0.8	27.9 ± 16.3 1.7–57.9	31.9 ± 15.8 3.7–64.2	40.2 ± 15.9 8.0–69.6	29.0 ± 19.9 1.4–73.3	16.5 ± 12.7 0.5–46.4	21.7 ± 15.1 0.9–55.3	32.8 ± 17.0 2.8–64.6

plants and legumes than males of the period, whereas males were eating significantly more C_4 plants and slightly (but significantly) more terrestrial mammal meat. As above, our hypothesis is supported by these results.

In contrast, in the Late Intermediate Period, the differences between male and female isotopic signatures were not found to be significant for any of the measures of interest (Table 4). Nonetheless, the manner in which the rather small isotopic differences between females and males propagated in the FRUITS simulation still resulted in significant differences in reconstructed dietary intake.

In the case of FRUITS Simulation A (Fig. 3 and Table 4), statistically significant differences (*t*-test, $p < 0.001$) in consumption of all three modeled food classes were observed. While males in the Late Intermediate Period were still eating significantly more C_4 and fewer C_3 plants than their female contemporaries, the differences were smaller (on the magnitude of 6–7%). Interestingly, in contrast to the Middle Period, females of the Late Intermediate Period would seem to have been consuming, on average, about 1% more meat than males of the same period. These results only partially support our hypothesis, in that Late Intermediate Period males, as expected, were consuming more C_4 plants than their female counterparts, but, counter to our prediction, they were also consuming less meat.

For FRUITS Simulation B (Fig. 4 and Table 4), Late Intermediate Period females and males did not appear to have significantly different patterns of terrestrial mammal meat consumption (*t*-test, $p = 0.003$), but still show highly significant differences (*t*-test, $p < 0.001$) for all classes of plants. Males of the Late Intermediate Period appear to have consumed significantly more C_4 plants (approximately 2%) and fewer C_3 plants and legumes (2% less for both classes) than females. It should be noted that this pattern of males consuming a larger proportion of C_4 plants holds true in both periods. As with Simulation A, our expectations of differences in C_4 plant consumption were confirmed, however meat consumption was not found to differ on the basis of sex.

Overall, both simulations found that male and female diet were more similar (to one-another) in the Late Intermediate Period than Middle Period for every single food group considered here. For example, the offset between male and female C_3 consumption was 18.6% in the Middle Period and a much smaller 6.0% in the Late Intermediate Period (Simulation A).

7.3. Sex between periods

Finally, individuals of the same sex of different periods were compared with one-another. Sample size for this analysis was the same as for the previous analysis of sex within periods.

Comparing Middle Period and Late Intermediate Period females revealed significant differences in all four isotopic measures. Females of the Late Intermediate Period had higher (more positive) values of $\delta^{13}C_{co}$, $\delta^{15}N_{co}$, and $\delta^{13}C_{ap}$ larger $\Delta^{13}C_{ap\text{-}co}$ values than their Middle Period equivalents (Table 4).

FRUITS Simulation A revealed a non-significant ($p = 0.005$) difference in meat consumption between Middle Period and Late Intermediate Period females, but significant differences ($p < 0.001$) in dietary plant consumption were noted (Fig. 3 and Table 4). The average Middle Period female consumed about 15% more C_3 and fewer C_4 plants than females of the Late Intermediate Period. These results do not support our contention that female diet would remain the same between periods.

FRUITS Simulation B comparing the average diet of Middle Period and Late Intermediate Period females indicated significant differences in consumption for all four stipulated food groups (Fig. 4 and Table 4). Late Intermediate Period females had significantly different protein diets (2% more terrestrial mammal products and 9% fewer legumes) and plant diets (6% fewer C_3 and 13% more C_4 plants) than females of the Middle Period. As above, these results do not confirm our hypothesis of dietary homogeneity over time.

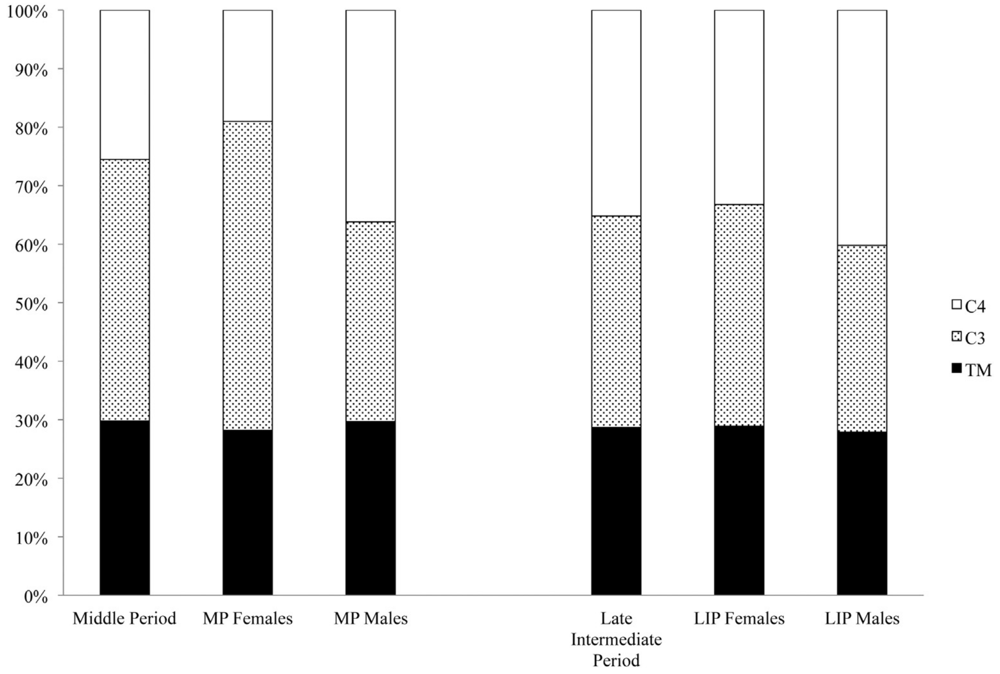

Fig. 3. Mean modeled contribution of three food classes (terrestrial animal meat, C_3 plants, C_4 plants) to diet of various sample subgroups (FRUITS Simulation A).

Comparing males of the two periods revealed less dramatic differences (Table 4). Only one of the four isotopic systems ($\delta^{15}N_{co}$) showed a statistically significant difference (Mann Whitney U, $p < 0.05$) between periods. Males of the Late Intermediate Period had significantly higher $\delta^{15}N_{co}$ values than males of the Middle Period. The Middle Period males had $\delta^{13}C_{co}$ and $\delta^{13}C_{ap}$ values that were at the highest end of the Middle Period range, and were more typical of individuals of the Late Intermediate Period.

Simulation A revealed statistically significant ($p < 0.001$) differences in modeled dietary input for all three food classes (Fig. 3 and Table 4). Males of the Late Intermediate Period were found to be consuming, on average, nearly 2% less meat than males of the Middle Period (with the observed increase in their $\delta^{15}N_{co}$ coming from a shift to more ^{15}N enriched C_4 plants), but the observed diachronic differences in plant consumption were more moderate than for females. The offset in C_3/C_4 plant consumption for males of the two periods was on the magnitude of 5% more C_4 and 5% less C_3 plants. The results of Simulation A support our hypothesis of diachronic change in meat and C_4 consumption.

Similarly, FRUITS Simulation B showed significant differences in three of the four categories of reconstructed dietary intake (Fig. 4 and Table 4).

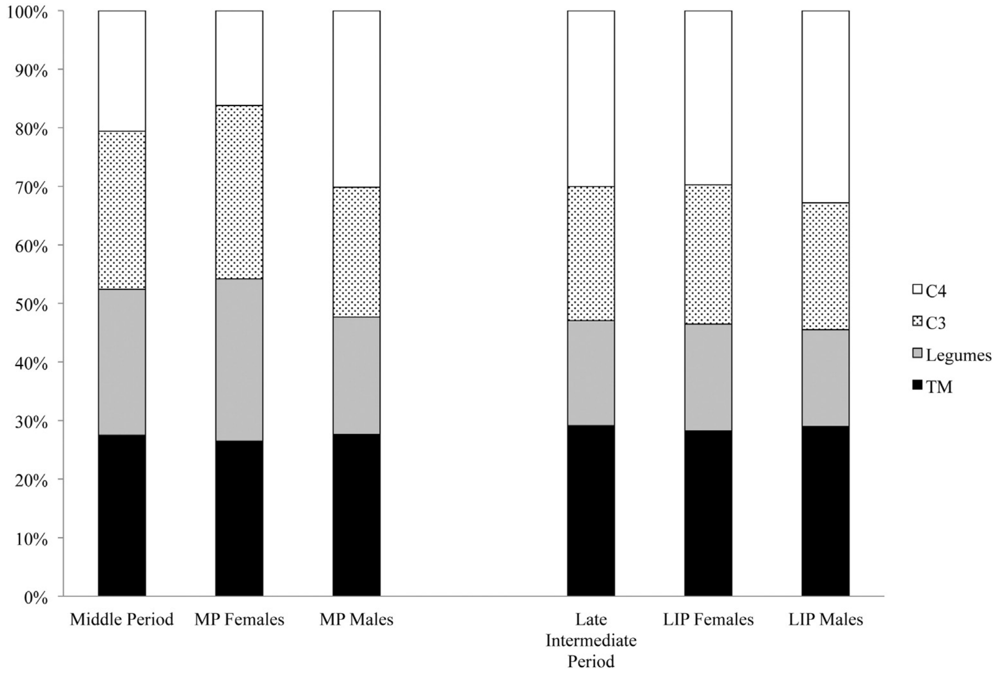

Fig. 4. Mean modeled contribution of four food classes (terrestrial animal meat, legumes, C_3 plants, C_4 plants) to diet of various sample subgroups (FRUITS Simulation B).

While there was no significant difference in the consumption of C_3 plants ($p = 0.08$) between males of the two periods, males of the Late Intermediate Period ate significantly ($p < 0.001$) more C_4 plants (about 3% more) and terrestrial mammals (1.5% more) and fewer legumes (3% less) than did their Middle Period counterparts. Like the simulations done for the whole sample, this simulation suggests that the increase in $\delta^{15}N_{co}$ between periods could be explained by both the decreased consumption of legumes and a modest increase in meat intake.

8. Discussion and conclusions

The disarticulation of the large interregional exchange networks of the south-central Andes at the end of the Middle Period significantly impacted the lifestyle of numerous populations. In the Atacama oases, the changes are visible both in the archaeological and bioarchaeological records. Accompanying evidence for the development of local leadership and stronger control over landscape and resources, previous research suggested changes in many aspects of life-style: the Late Intermediate Period saw an increase in interpersonal violence (Torres-Rouff and Costa, 2006); a decrease in average nutritional status (Neves and Costa, 1998); a reduction in biological diversity that could be the results of diminished influx of people into the oases (Varela and Cocilovo, 2009); and possibly changes in some aspects of body use, tied to activities affecting the vertebral column (López-Barrales et al., 2015). Therefore, it would seem that the broader changes observed during the Late Intermediate Period were affecting basic aspects of local life-style and social dynamics, including the re-organization of local elites.

In the context of the current study, it is notable that even though the archaeological record does not show evidence of strong changes in available foodstuffs, studies of the skeletal remains suggest important changes in diet between the Middle and Late Intermediate Period (Costa et al., 2004; Hubbe et al., 2012). The results presented here strongly support this assertion, and help to illuminate the specific nature of dietary changes during the Late Intermediate Period. Given the role that differential access to food has in the definition of social hierarchy and the value food has as one of the central determinants of social inequality among human societies, our results also complement previous discussions about the nature of social organization in the Atacama oases in the past (e.g., Torres-Rouff, 2008, 2011).

A general appraisal of dietary makeup in the Quitor samples indicates a diet largely composed of plants, with significant shifts in C_3/C_4 contributions (over time and between the sexes), and more significant shifts (albeit in smaller percentages) in dietary protein makeup. The overall diet fits models with a high contribution from C_3 carbohydrates, which is not surprising given the prominence of local C_3 plants (e.g. algarrobo, *Prosopis chilensis*) that were commonly consumed in ground form and were an Atacameño dietary staple across periods (Llagostera, 2004). However, C_4 plants, meat and possibly legumes also played important roles in local diet. These overall results are relevant because they shift attention away from maize and meat, which have repeatedly been used to explain diet composition in previous studies (e.g. Costa et al., 2004; Hubbe et al., 2012; Neves and Costa, 1998).

Most pertinent, though, is the evidence of an important shift in dietary composition between the Middle and Late Intermediate Periods. Regarding sources of carbohydrates, Middle Period isotopic evidence indicates a substantial degree of dietary variability and patterned internal variation in food intake. There is more variance in diet among individuals at this time than during the Late Intermediate Period, as is reflected higher standard deviations for $\delta^{13}C_{co}$ and $\delta^{13}C_{ap}$. This higher variance flows partially from differences between the sexes, with females consuming fewer C_4 plants (presumably maize) than males. Although a similar pattern is observed during the Late Intermediate Period, differential access to maize is less pronounced, as a result of increased C_4 contributions to female diets (Table 4), while males show less dramatic changes in both isotope values and the estimated percentage of C_4.

These preliminary results fit with previous results that showed that sex differences were significant during the Middle Period (Hubbe et al., 2012). It has been suggested that this period was marked by increased social inequality, with a well-defined local hierarchy that resulted from different *ayllus* and/or families in the Atacama oases having stronger ties to the interregional exchange networks of the time (Torres-Rouff 2011). Arguably, this structured hierarchy was also reflected in greater gender inequalities during this period (Hubbe et al., 2012). Our results fit with these suggestions by indicating differences in dietary composition between periods and sexes and demonstrating the potentially important role of maize consumption in the experience of these social inequalities. Given the connection between maize and males suggested by our data for Quitor, it is possible to speculate that men preferentially accessed maize. Although the mode of ingestion cannot be deciphered, it is possible that the ritual consumption of fermented maize in the form of *chicha* accounts for some of the differences observed here. *Chicha* is an important component of ritual life in the South Central Andes as a whole (e.g. Pardo and Pizzaro, 2005), and still present in current local traditions (Barthel, 1986; Moyano, 2010). Archaeological evidence for drinking vessels is also prominent in the Atacama oases (Llagostera, 2004). Therefore, we argue that maize, possibly in form of *chicha*, may have been tied to social status during the Middle Period, and that the decrease in visible diet-based sex differences during the Late Intermediate Period may reflect a reduction in the differential access to maize among the local population at this time.

The sources of the protein intake difference, on the other hand, are harder to explain, especially due to the potential role that legumes might have played in local diet. Previous studies have suggested that the Middle Period was marked by an increase in access to meat by males (Hubbe et al., 2012). While some of our results initially support this claim, and FRUITS Simulation A (without legumes) suggests more meat was being consumed by men during the Middle Horizon, this trend disappears in Simulations B (with legumes). The inclusion of legumes as a food source suggests potential dietary combinations among the Quitor populations that have not been considered previously. The traditional assumption (Hubbe et al., 2012; Santana-Sagredo et al., 2015), that variation in $\delta^{15}N$ was solely a product of differences in meat consumption is belied by the inclusion in the foodweb and dietary solutions of legumes, a (relatively) protein rich and ^{15}N depleted plant foodstuff. Indeed, models with changes in legume consumption (between periods or sexes) but no change in meat intake, are as efficient in explaining the data as models with meat only. In this regard, then, the results of FRUITS Simulation B provide an interesting baseline for future study, in that these results might be tested against a re-analysis of caries data, which could take into account the different cariogenic potential of legumes and meat, as well as the more often-considered carbohydrate rich plant foods. Furthermore, these results point to the potential importance of legumes in the local diet, something that has not been explored in the local archaeological record. As such they highlight the need for more detailed archaeobotanical studies in the area.

Finally, it is worth noting that our results are in line with the isotopic data from Quitor 6 Tardío published by Santana-Sagredo et al. (2015). A comparison of those individuals with the Quitor 6 Tardío individuals presented here revealed that the two subsamples drawn from the same cemetery were statistically indistinguishable from one another for all four isotope systems (Mann-Whitney U Tests, $p > 0.14$). We did not include these data in our analyses and interpretations due to potential inter-laboratory differences stemming from differences in sample pretreatment and extraction protocols (Pestle et al., 2014). Nonetheless, the fact that our results are coherent with these isotopic data reinforces the conclusions drawn from our analysis and simulations.

In conclusion, the use of linear mixture modeling in the present application facilitated the quantification of foodstuff inputs in a probabilistic and uncertainty-integrated manner, and enabled dietary reconstruction in meaningful terms (i.e. discussion of food groups rather than macronutrients), allowing for a more nuanced interpretation of dietary composition in prehistoric Atacameño populations. The broad social changes between the Middle and Late Intermediate Period had a significant impact on dietary composition. We argue that this shift was related not only to access to meat, as previously suggested, but also strongly tied to access to maize products, which may have been used to reinforce social status and gender inequalities during the Middle Horizon.

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References

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

Ambrose, S.H., 1993. Isotopic analysis of Paleodiets: methodological and interpretive considerations. In: Sanford, M.K. (Ed.), Investigation of Ancient Human Tissue Chemical Analyses in Anthropology. Gordon and Breach, Langhorne, PA, pp. 59–130.

Ambrose, S.H., 2000. Controlled diet and climate experiments on nitrogen isotope ratios of rats. In: Ambrose, S.H., Katzenberg, M.A. (Eds.), Biogeochemical Approaches to Paleodietary Analysis. Kluwer Academic/Plenum Publishers, New York, pp. 243–259.

Arriaza, B., Ogalde, J.P., Chacama, J., Standen, V., Huamán, L., Villanueva, F., 2015. Estudios de almidones en Queros de Madera del Norte de Chile relacionados con el consumo de chicha durante el Horizonte Inca. Estudios Atacameños. 50, pp. 59–84.

Barthel, T., 1986. El agua y el festival de primavera entre los Atacameños. Allpanchis. 28, pp. 1–19 (1957).

Berenguer, J., 2004. Tráfico de Caravanas, Interacción Interregional Y Cambio Cultural en la Prehistoria Tardía del Desierto de Atacama. Ediciones Sirawi, Santiago.

Berenguer, J., Dauelsberg, P., 1989. El Norte Grande en la orbita de Tiwanaku (400 a 1.200 d.C.). In: Hidalgo, L.J., Schiappacasse, F.V., Niemeyer, F.H., Aldunate, del S.C., Solimano, R.I. (Eds.), Culturas de Chile: Prehistoria desde sus Orígenes hasta los Albores de la Conquista. Editorial Andres Bello, Santiago, pp. 129–180.

Buikstra, J.E., Ubelaker, D.H. (Eds.), 1994. Standards for Data Collection from Human Skeletal Remains. Arkansas Archaeological Survey Research Series, Fayetteville.

Buzon, M.R., Eng, J.T., Lambert, P., Walker, P.L., 2005. Bioarchaeological methods. In: Maschner, H., Chippindale, C. (Eds.), Handbook of Archaeological Methods Vol. II. Altamira Press, Lanham, MD, pp. 871–918.

Costa, M.A., 1988. Reconstitución física y cultural de la población tardía del cementerio de quitor-6 (San Pedro de Atacama). Estudios Atacameños 9, 99–126.

Costa, M.A., Neves, W.A., Hubbe, M., 2004. Influencia de Tiwanaku en la calidad de vida biológica de la población prehistórica de San Pedro de Atacama. Estudios Atacameños. 27, pp. 103–116.

Cuellar, A.M., 2013. The archaeology of food and social inequality in the Andes. J. Archaeol. Res. 21, 123–174.

Da-Gloria, P., Neves, W.A., Costa, M.A., Bartolomucci, R., 2011. Nonspecific infectious diseases in prehistoric San Pedro de Atacama, Northern Chile. Chungará 43 (235–146).

DeNiro, M.J., Epstein, S., 1981. Influence of diet on the distribution of nitrogen isotopes in animals. Geochim. Cosmochim. Acta 45, 341–351.

DeNiro, M.J., Hastorf, C., 1985. Alteration of ^{15}N/^{14}N and ^{13}C/^{12}C ratios of plant matter during the initial stages of diagenesis: studies using archaeological specimens from Peru. Geochim. Cosmochim. Acta 49, 97–115.

Erickson, C.L., 1999. Neo-environmental determinism and agrarian 'collapse' in Andean prehistory. Antiquity. 73, pp. 634–642.

Fernandes, R., Nadeau, M.-J., Grootes, P.M., 2012. Macronutrient-based model for dietary carbon routing in bone collagen and bioapatite. Archaeol. Anthropol. Sci. 4, 291–301.

Fernandes, R., Millard, A.R., Brabec, M., Nadeau, M.-J., Grootes, P., 2014. Food reconstruction using isotopic transferred signals (FRUITS): a Bayesian model for dietary reconstruction. PLoS One 9 (2), e87436.

Fernandes, R., Grootes, P., Nadeau, M.-J., Nehlich, O., 2015. Quantitative diet reconstruction of a Neolithic population using a Bayesian mixing model (FRUITS): the case study of Ostorf (Germany). Am. J. Phys. Anthropol. 158, 325–340.

Froehle, A.W., Kellner, C.M., Schoeninger, M.J., 2012. Multivariate carbon and nitrogen stable isotope model for the reconstruction of prehistoric human diet. Am. J. Phys. Anthropol. 147, 352–369.

Goldstein, P.S., 2005. Andean Diaspora: The Tiwanaku Colonies and the Origins of South American Empire. University Press of Florida, Gainesville, FL.

Hare, P.E., Fogel, M.L., Stafford, T.W., Mitchell, A.D., Hoering, T.C., 1991. The isotopic composition of carbon and nitrogen in individual amino acids isolated from modern and fossil proteins. J. Archaeol. Sci. 18, 277–292.

Hastorf, C.A., 1991. Gender, space, and food in prehistory. In: Conkey, M., Gero, J.M. (Eds.), Engendering Archaeology: Women and Prehistory. Basil Blackwell, Oxford, pp. 132–163.

Hopkins, D.T., 1981. Effects of variations in protein digestibility. In: Bodwell, C.E., Adkins, J.S., Hopkins, D.T. (Eds.), Protein Quality in Humans: Assessment and in vitro Estimation. AVI Publishing, Westport, CT, pp. 178–181.

Howland, M.R., Corr, L.T., Young, S.M.M., Jones, V., Jim, S., Van Der Merwe, N.J., Mitchell, A.D., Evershed, R.P., 2003. Expression of the dietary isotope Signal in the Compound-Specific ^{13}C values of Pig bone lipids and amino acids. Int. J. Osteoarchaeol. 13, 54–65.

Hubbe, M., Oviedo, M., Torres-Rouff, C., 2011. El estado de conservación de la colección osteológica Gustavo Le Paige y su contextualización cronológica. Estudios Atacameños. 41, pp. 29–44.

Hubbe, M., Torres-Rouff, C., Neves, W.A., King, L.M., Da-Gloria, P., Costa, M.A., 2012. Dental health in Northern Chile's Atacama oases: evaluating the Middle Horizon (500–1000 CE) impact on local diet. Am. J. Phys. Anthropol. 148, 62–72.

Janusek, J.W., 2004. Identity and power in the ancient Andes: Tiwanaku cities through time. Routledge, London.

Keeling, C.D., Mook, W.G., Tans, P.P., 1979. Recent trends in the ^{13}C/^{12}C ratio of atmospheric carbon dioxide. Nature 277, 121–123.

Knudson, K.J., Torres-Rouff, C., Stojanowski, C., 2015. Investigating human responses to political and environmental change through paleodiet and paleomobility. Am. J. Phys. Anthropol. 157 (2), 179–201.

Krueger, H.W., 1991. Exchange of carbon with biological apatite. J. Archaeol. Sci. 18, 355–361.

Latcham, R.E., 1938. Arqueología De La Región Atacameña, Prensa de la Universidad de. Chile, Santiago.

Le Paige, G., 1964. Los cementerios del período agroalfarero de San Pedro de Atacama. Anales de la Universidad del Norte, Antofagasta. 3, pp. 43–93.

Lee-Thorp, J.A., 1989. Stable Carbon Isotopes in Deep Time: The Diets of Fossil Fauna and Hominids. University of Cape Town, Cape Town, South Africa, Department of Archaeology.

Lee-Thorp, J.A., 2008. On isotopes and old bones. Archaeometry 50, 925–950.

Llagostera, A., 1996. San Pedro De Atacama: Nodo De Complementariedad Reticular. Estudios y Debates Regionales Andinos 96, 17–42.

Llagostera, A., 2004. Los Antiguos Habitantes del Salar de Atacama: Prehistoria Atacameña. Pehuen, Santiago.

Llagostera, A., Costa, M.A., 1999. Patrones de asentamiento en la época Agroalfarera de San Pedro de Atacama (norte de Chile). Estudios Atacameños. 17, pp. 175–206.

Longin, R., 1971. New method of collagen extraction for radiocarbon dating. Nature 230, 241–242.

López-Barrales, R., Hubbe, M., Aspillaga, E., Niemeyer, H.M., 2015. Niveles de cortisol en cabellos de poblaciones prehispánicas de San Pedro de Atacama, Norte de Chile. Chungará 47, 679–689.

Miller, M.J., Capriles, J.M., Hastorf, C.A., 2010. The fish of lake Titicaca: implications for archaeology and changing ecology through stable isotope analysis. J. Archaeol. Sci. 37, 317–327.

Moore, J.W., Semmens, B.X., 2008. Incorporating uncertainty and prior information into stable isotope mixing models. Ecol. Lett. 11, 470–480.

Morrison, D.J., Dodson, B., Slater, C., Preston, T., 2000. ^{13}C natural abundance in the British diet: implications for ^{13}C breathe tests. Rapid Commun. Mass Spectrom. 14, 1312–1324.

Mostny, G., 1949. Ciudades Atacamenas. Boletín del Museo Nacional de Historia Natural (Santiago de Chile) XXIV, pp. 125–211.

Moyano, R., 2010. La mano de Dios en Socaire: estudio de un calendario agrícola en Atacama, norte de Chile. Unpublished Masters Thesis. Escuela Nacional de Antropología e Historia, México, D.F.

Muñoz, E., 1984. Restauración del Pucara de Quitor. Estudios Atacameños. 7, pp. 191–197.

Neves, W.A., Costa, M.A., 1998. Adult stature and standard of living in the prehistoric Atacama Desert. Curr. Anthropol. 39, 278–281.

Núñez, L., 1991. Cultura Y Conflicto en Los Oasis de San Pedro de Atacama. Editorial Universitaria, Santiago.

Núñez, L., 2007. Vida y Cultura en el Oasis de San Pedro de Atacama. Editorial Universitaria, Santiago.

Núñez, L., McRostie, V., Cartajena, I., 2009. Consideraciones sobre la recolección vegetal y la horticultura durante el formativo temprano en el Sureste de La Cuenca de Atacama. Darwiniana. 47, pp. 56–75.

Ortloff, C., Kolata, A.L., 1993. Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku state. J. Archaeol. Sci. 20, 195–221.

Pardo, O., Pizzaro, J.L., 2005. La Chicha en El Chile Precolombino. Mare Nostrum, Santiago.

Pestle, W.J., 2010. Diet and Society in Prehistoric Puerto Rico, an Isotopic Approach, Department of Anthropology. University of Illinois at Chicago.

Pestle, W.J., Colvard, M., 2012. Bone collagen preservation in the tropics: a case study from ancient Puerto Rico. J. Archaeol. Sci. 39, 2079–2090.

Pestle, W.J., Crowley, B.E., Weirauch, M.T., 2014. Quantifying inter-laboratory variability in stable isotope analysis of ancient skeletal remains. PLoS One 9 (7), e102844.

Pestle, W.J., Hubbe, M., Smith, E.K., Stevenson, J.M., 2015a. A linear model for Predicting δ^{13}C$_{\text{protein}}$. Am. J. Phys. Anthropol. 157, 684–703.

Pestle, W.J., Torres-Rouff, C., Gallardo, F., Ballester, B., Clarot, A., 2015b. Mobility and exchange among marine hunter-gatherer and agropastoralist communities in the formative period Atacama Desert. Curr. Anthropol. 56, 121–133.

Pimentel, G., Montt, I., Blanco, J., Reyes, A., 2007. Infraestructura y prácticas de movilidad en una ruta que conectó el altiplano boliviano con San Pedro de Atacama (II Región, Chile). In: Nielse, A.E., Rivolta, M.C., Seldes, V., Vásquez, M.M., Mercolli, P.H. (Eds.), Producción y Circulación Prehispánicas de Bienes en el sur Andino. Editorial Brujas, Córdoba, pp. 351–382.

Rivera, M., 2008. The archaeology of Northern Chile. In: Silverman, H., Isbell, W. (Eds.), Handbook of South American Archaeology. Springer, New York, pp. 963–997.

Santana-Sagredo, F., Lee-Thorp, J.A., Schulting, R., Uribe, M., 2015. Isotopic evidence for divergent diets and mobility patterns in the Atacama Desert, Northern Chile, during the LIP (900 CE–1450). Am. J. Phys. Anthropol. 156, 374–387.

Schiappacasse, V., Castro, V., Niemeyer, H., 1989. Los desarrollos regionales en el Norte Grande. In: Hidalgo, L.J., Schiappacasse, F.V., Niemeyer, F.H., Aldunate, del S.C., Solimano, R.I. (Eds.), Culturas de Chile: Prehistoria Desde sus Orígenes Hasta los Albores de la Conquista. Editorial Andres Bello, Santiago, pp. 181–220.

Schoeninger, M.J., DeNiro, M.J., 1984. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochim. Cosmochim. Acta 48, 625–639.

Sponheimer, M., Robinson, T., Ayliffe, L., Roeder, B., Hammer, J., Passey, B., West, A., Cerling, T., Dearing, D., Ehleringer, J., 2003. Nitrogen isotopes in mammalian herbivores: hair Δ^{15}N values from a controlled feeding study. Int. J. Osteoarchaeol. 13, 80–87.

Stock, B.C., Semmens, B.X., 2013. Mixsiar, version 1.0. http://Conserver.Iugo-Cafe.Org/User/Brice.Semmens/Mixsiar.

Stovel, E.M., 2005. The archaeology of identity construction: ceramic evidence from Northern Chile. In: Funari, P., Zarankin, A., Stovel, E.M. (Eds.), Global Archaeological Theory. Kluwer Academic/Plenum, New York, pp. 145–166.

Thomas, C., Benavente, A., Cartajena, I., Serracino, G., 1995. Topater, un cementerio Temprano: una aproximación simbólica. Hombre y Desierto. 9, pp. 159–170.

Tiesezen, L.L., 1981. Natural variation in the carbon isotope values of plants: implications for archaeology, ecology, and paleoecology. J. Archaeol. Sci. 18, 227–248.

Tieszen, L.L., Chapman, M., 1992. Carbon and Nitrogen Isotopic Status of the Major Marine and Terrestrial Resources in the Atacama Desert of Northern Chile. Proceedings of the First World Congress on Mummy Studies. Museo Arqueológico y Etnográfico de Tenerife, Tenerife, pp. 409–425.

Torres-Rouff, C., 2008. The influence of Tiwanaku on life in the Chilean Atacama: mortuary and bodily perspectives. Am. Anthropol. 110, 325–337.

Torres-Rouff, C., 2011. Hiding inequality beneath prosperity: patterns of cranial injury in middle period San Pedro De Atacama, Northern Chile. Am. J. Phys. Anthropol. 146, 28–37.

Torres, C.M., Conklin, W.J., 1995. Exploring the San Pedro de Atacama/Tiwanaku relationship. In: Dransart, P. (Ed.), Andean Art: Visual Expression and Its Relation to Andean Beliefs and Values. Avebury, Aldershot, pp. 78–108.

Torres-Rouff, C., Costa, M.A., 2006. Interpersonal violence in prehistoric San Pedro de Atacama, Chile: behavioral implications of environmental stress. Am. J. Phys. Anthropol. 130, 60–70.

Torres-Rouff, C., Knudson, K.J., Pestle, W.J., Stovel, E.M., 2015. Tiwanaku influence and social inequality: a bioarchaeological, biogeochemical, and contextual analysis of the Larache cemetery, San Pedro De Atacama, Northern Chile. Am. J. Phys. Anthropol. 158, 592–606.

United States Department of Agriculture, 2013. National nutrient database for standard reference, release 27. Available: http://www.ars.usda.gov/Services/ docs.htm?docid=8964 Accessed October 11, 2015.

Uribe, M., 2002. Sobre Alfarería, cementerios, fases y procesos durante la prehistoria Tardía de Atacama (800–1600 DC). Estudios Atacameños. 21, pp. 7–31.

Varela, H.H., Cocilovo, J.A., 2009. Microevolución en San Pedro de Atacama (norte de Chile): el cementerio de Quitor. Lat. Am. Antiq. 20, 333–342.

Warinner, C., Tuross, N., 2009. Alkaline cooking and stable isotope tissue-diet spacing in swine: archaeological implications. J. Archaeol. Sci. 36, 1690–1697.

World Health Organization, 2007. Protein and Amino Acid Requirements in Human Nutrition, WHO Technical Report Series no. 935. WHO Press, Geneva.