



Models for paleodietary research: Three case-studies from arid and semi-arid environments in Northwest Argentina

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ABSTRACT

In this article, we present three case-studies of paleodietary reconstruction from Prehispanic agropastoralist societies located in the arid and semi-arid zones of North western Argentina. These three examples include the micro-region of Antofagasta de la Sierra, located in the *puna* of the Catamarca Province; the *puna* archaeological site of Río Doncellas; and the pre-*puna* archaeological site of Los Amarillos. These latter two sites are situated in the Jujuy Province. Here we present a quantitative approximation that provides a relative hierarchy of plant versus animal resource consumption. In so doing, we aim to overcome the uncertainty generated by previous studies on this theme. To this end, we employed the mixed Bayesian model FRUITS (Food Reconstruction Using Isotopic Transferred Signals), which utilises three different proxies – $\delta^{13}\text{C}_{\text{collagen}}$, $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{15}\text{N}$. This model confirmed the importance of maize vis-à-vis other resources at Los Amarillos, its lesser relevance within the Antofagasta de la Sierra context, and its negligible presence at the Río Doncellas site. Likewise, within the resource hierarchy of the *puna* economy – *Solanum tuberosum* – a seemingly, marginal crop, in contrast to camelids, gained greater traction. In this manner, we can detect the different nutritional strategies employed by the Prehispanic agropastoralist economies of the region.

1. Introduction

During Pre-Hispanic times and across coeval periods, the existing ecological variability in North-western Argentina (NOA) would have presented a broad variety of economic possibilities. These varied economic life-ways would have resulted in different productive emphasis and the exploitation of certain resources to the detriment of others – for example, the cultivation of meso-thermal plants, such as maize, versus micro-thermal species, such as tubers and pseudo-cereals (Killian Galván, 2015). Likewise, cultivation choice could well have underpinned the social strategies employed in the distribution of these resources (Killian Galván, 2015).

One of the analysis proposed to establish the existence of different patterns of consumption in societies of the past, is that of stable isotope of carbon and nitrogen extracted from human remains. Thus, in this paper, the implications of isotope analysis towards the reliable reconstruction of human diet are examined. To this effect, three case-studies from arid and semi-arid regions with human isotope databases are presented. These are: the micro-region of Antofagasta de la Sierra, Catamarca; the archaeological site of Río Doncellas, Jujuy; and the archaeological site of Los Amarillos, Quebrada de Humahuaca, Jujuy (Fig. 1). These cases were selected because it allowed us to compare the

cereal production economy from areas where its cultivation might have been difficult. On this basis, this research discusses the role of cereal production in the societies of NOA macro-region.

In the case of Antofagasta de la Sierra (ANS), archaeological research in this micro-region allows us to propose – based on different lines of evidence – changes in economic strategies throughout the Late Holocene. In this respect, the consolidation of agro-pastoral groups is postulated, from ca. 2500 years BP. These groups progressively increased plant cultivation, leading from intensive to extensive strategies in agricultural production, a process that would have been further consolidated by the arrival of the Inca Empire to the region (Olivera, 1988). Stable isotope samples were obtained from 14 individuals from different agro-pastoral periods across the Late Holocene. Results, taking in account isotopic values of local and neighbouring resources, indicate that in most of cases, consumption of C_4 plant species such as maize (*Zea mays*) and amaranth (*Amaranthus caudatus*) was less important in relation to other resources, while meat resources from lower elevations within the *puna* eco-region were of a higher significance (Killian Galván et al., 2016a).

The Río Doncellas Archaeological Site (RD) is one of the best-known sites of the Late period (ca. 1000 CE–1450 CE) within the Argentinean Puna (Alfaro de Lanzone, 1988; Pérez and Killian Galván, 2011; Pérez

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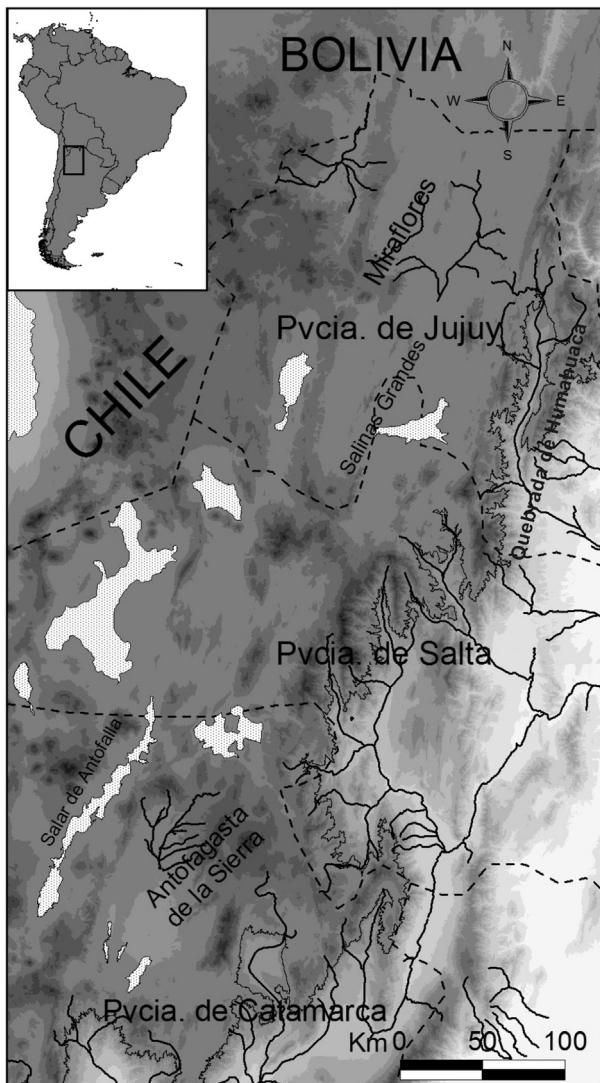


Fig. 1. Map of Puna and Pre-puna areas in Northwest Argentina (Catamarca Province and Jujuy Province), showing the location of the archaeological areas of research: Antofagasta de la Sierra, Miraflores (Archaeological site Río Doncellas) and Quebrada de Humahuaca (Archaeological site Los Amarillos).

de Micou, 1996). Based on research undertaken at the site between the decades of 1940 and 1970, it has been proposed that the population which occupied the area had camelid herding as their main economic activity, but also practiced extensive crop agriculture. From RD, 13 human individuals were sampled for stable isotopes analysis (Killian Galván et al., 2016b). The basis for paleodietary inference were the food resources – plant and fauna – found in the archaeological record, as well as modern comparative data from farms located in the study area (Abra Pampa, Cochinoca, Jujuy). The results indicate that maize (*Zea mays*) was less important than other plant resources within the diet. This contradicts the expectations generated from the macro-botanical evidence of the site, and the cultivation terraces that surround it. Similarly, camelids seemed to have been widely exploited; this was coherent with the modern importance of meat production within the region. These results allowed us to assert that cereal production did not predominate over other resources (Killian Galván et al., 2016b).

Finally, a sample of 20 adult human individuals from different sectors of the site of Los Amarillos, dating to the Regional Developments Period (ca. 1000 CE–1450 CE) and Inca Period (ca. 1430–1536 CE) were analysed. It has been postulated, that for late Prehispanic societies the daily food of these populations might have

been deficient, despite its availability due to an economic system based on the intensification of both meat and plant production. This has been suggested by the zooarchaeological analyzes and the bioarchaeological study of human skeletal series from different late sites of Quebrada de Humahuaca (Mercolli and Seldes, 2007; Seldes, 2007). Based on the data collected, researchers postulated that, despite the presumed greater availability of food resulting from agricultural (where maize stands out) and herding (camelid exploitation) intensification, the consumption of resources – particularly those of animal origin – could be unequal or inadequate (Mercolli and Seldes, 2007). In this case, our aim was to determine the predominant resources used in their diets, against the background of the regional plant and animal isotope (Killian Galván et al., 2016c). We also evaluated the internal variability of the sample, taking into consideration the location of the individuals in the site. The results indicate a balanced diet of meat resources located at levels below 3.900 m.a.s.l., and C_4 photosynthetic pathway plants (maize and amaranth). On the other hand, the consideration of the contextual data on the burials revealed little variability in dietary patterns (Killian Galván et al., 2016c).

All the samples, from across the three case-studies, were analysed using the same methodology: in all the cases, the interpretative methods employed were semi-quantitative and based on the comparison of human isotope values with pre-defined isotope ranges associated with types of diet. Thus, these studies have not fully quantitatively defined the importance of animal versus plant resources (Killian Galván et al., 2016a; Killian Galván et al., 2016b; Killian Galván et al., 2016c). Nevertheless, we build upon previous work in these three areas, by quantitatively reconstructing the diet of the population using the Bayesian mixing model FRUITS (Fernandes et al., 2014). Estimates generated by FRUITS include the relative calorie contribution from available food groups, levels of protein intake, and the relative protein contribution from each food group. Also, given the possibility of including a priori information as restrictions on the relative intake of macronutrients, the results thus rendered can be more realistic. Therefore, the aim of the present paper is to solve equifinality problems generated by an earlier methodology that did not consider the importance of macronutrient concentrations in each set of foods. We also differentiate between assemblages that exhibit similar isotopic signals, consequently establishing which set of resources supported the economy in each case: maize production, camelid exploitation or micro-thermal plant resources, such as high-altitude tubers.

2. Material and site description

2.1. Antofagasta de la Sierra (AS, Catamarca province)

Antofagasta de la Sierra (AS, Catamarca province) is in a typical Puna environment (Fig. 1, Table 1), with rainfall averaging 124 mm per year. The area presents a highly heterogeneous landscape, with three micro-environments and therefore different types of resources available: a) the basin bottom (3400–3550 m.a.s.l.) offers the best possibilities for agriculture with its open topography and water availability; b) the intermediate sectors (3550–3800 m.a.s.l.), which include the lower and middle sections of the Punilla River tributaries, with its availability of fodder, water and land suitable for agro-pastoral production, but of lesser extent and importance than the basin bottom, it also includes big extensions of shrubs; c) the high ravines (3800–4600 m.a.s.l.) including the narrow ravines of the middle and upper sections of the Punilla River tributaries, with permanent water and diverse fodder resources suitable for hunting and grazing activities (Olivera and Podestá, 1993).

The exploitation of all these areas, either in an articulated manner, or with a greater emphasis on one resource would have varied over time, and with it, presumably, the food consumption strategies employed (Olivera, 1992). For the Initial Period (ca. 3000–1700 years BP), an economic model that combined llama (*Lama glama*) pastoralism with agriculture has been suggested. In this model pastoralism was the main

Table 1
Isotope values and standard deviations of skeletal samples from de Río Doncellas.

n	Sample	Sex	Age range	AIE	$\delta^{13}\text{C}$ (± 0.2)	$\delta^{15}\text{N}$ (± 0.2)	C/N	AIE	$\delta^{13}\text{C}$ (± 0.1)
1	1° molar	M	Adult	27,640	-16.3	12.9	3.2	30,514	-11.3
2	Skull	I	Adult	27,521	-15.9	12.2	3.3	30,515	-12.2
3	2° molar	F	Adult	27,506	-16.1	12.3	3.2	30,516	-10.9
4	Rib	F	Adult	19,234	-15.0	12.5	3.2	522	-11.8
5	Rib	I	Youth	19,235	-15.7	11.7	3.2	515	-11.6
6	Rib	I	Adult	19,236	-17.2	11.8	3.2	514	-13.7
7	Skull	I	Adult	19,237	-15.8	12.3	3.2	519	-12.2
8	Rib	M	Adult	19,238	-14.6	13.5	3.2	521	-12.5
9	Rib	F	Adult	19,239	-14.8	11.8	3.2	513	-13.1
10	Rib	I	Adult	UW 93931*	-15.5	14.4	3.1	518	-12.9
				Mean	-15.7	12.5			-12.2
				St. dev.	0.5	0.7			0.5

economic focus, complemented by small-scale agriculture. On the other hand, vicuña hunting (*Vicugna vicugna*) was an important component in the subsistence of these groups and perhaps it was the greatest contributor of meat protein to human diet (Olivera, 1988; Olivera and Grant, 2008). At 1700 years BP, there is an increase in the importance of agricultural production, although undeniably camelid pastoralism still played a crucial role in the economy (Olivera and Podestá, 1993). During the period ca. 1200–1000 years B.P., there is a further intensification and expansion of agricultural production. This agricultural intensification takes advantage of fertile soils and hydrological improvements such as the construction of water canals (Tchilinguirian and Olivera, 2000).

Following at ca. 700 years BP, there were modifications in the social and political organization. During this subsequent period, the importance of plant cultivation continues to increase, this is evidenced by the making of storage ceramics (Olivera and Vigliani, 2000–2002), the large quantity of corn marlins found at Quebrada de Petra (Olivera and Vigliani, 2000–2002), and the greater expediency noted in the production of lithic sets (Elías, 2012). Likewise, in the faunal assemblages, the importance of llama continues, but throughout hunting also persists. Finally, with the Inca occupation (ca. 1480–1532 CE), changes were introduced in the crop infrastructure that gave rise to an even more complex agricultural production system (Tchilinguirian and Olivera, 2000).

For the study presented here, it is important to note that macro and micro (microfossils and vegetal residues) botanical data of local production (*Zea mays*, *Chenopodium quinoa*, *Phaseolus*, *Prosopis* sp.), as well as plants of possible foreign origin (*Geoffroea decorticans*) (synthesis in Gasparotti and Haros, 2015), have been found at archaeological sites from the basin and intermediate sectors, while wild and domestic camelid remains have been found throughout the study area and at all altitudes.

2.2. The archaeological site of Río Doncellas (RD, Cochínoca Department, Province of Jujuy)

The archaeological site of Río Doncellas (RD, Cochínoca Department, Province of Jujuy) is in the Guayatayoc-Miraflores basin (22° 49' 12,28" S and 66° 03' 54,89" W) (Fig. 1, Table 2). It is also located in a typical Puna environment (Alfaro de Lanzone, 1988), at 3500 m.a.s.l., with annual precipitations of less than 350 mm, often the result of torrential rains (Tchilinguirian, 2009). The altitude and topography affect average temperatures; these can be lower than 10 °C, with a high degree of variation, especially during the winter (Bianchi et al., 2005; Ottonello de Reinoso and Ruthsatz, 1982). RD comprises different sectors: pit-houses near the entrance, the main village, and the outcrop sector on both sides of the village (North and South). These last two had funerary structures, the sampled individuals came from this sector. The village is surrounded by field terraces, caves and rockshelters, all of them within a distance of 5 km. Radiocarbon dating

brackets an occupation dating to between ca. 740 and 310 years BP (Alfaro de Lanzone, 1988; Fuchs and Varela, 2013; Fuchs et al., 2015; Pérez de Micou, 1996). However, a Spanish coin dated to the year 1677 found on the site (Vignati, 1938), among other finds, confirms that the village was also occupied during the Hispanic Period

Considering the economic agropastoralist strategy in place, on the one hand, the area is fit for primary and secondary (wool and transport) exploitation of camelids (Albeck and Zaburlín, 1996; Pérez and Killian Galván, 2011; Pérez de Micou, 1996; Yacobaccio and Madero, 2001). Evidence such as crop terraces, crop fields and hydraulic systems suggest a successful agricultural economy (Alfaro de Lanzone, 1988; Ottonello de García Reinoso, 1973).

The importance of understanding the place of each component inside an economic system lies in establishing if the surplus production of maize crops (*Zea mays*) guaranteed the high demography postulated for the period, as well as the social hierarchy inferred for this area at that time by some researchers (Tarragó, 2000). Even though the environmental conditions of high aridity and altitude are more benevolent for micro-thermal vegetables, maize has been proposed as a fundamental part of the Prehispanic economy of the area, given the ubiquity of macro-botanical evidence for this species (Alfaro de Lanzone, 1988). Recently, a sample of maize recovered during the last excavations on the site was analysed and eight separate subspecies were been identified (Killian Galván et al., 2014). This shows a high degree of bio-variability within the assemblage.

2.3. The archaeological site of Los Amarillos

The archaeological site of Los Amarillos (23°21'43,53" S, 65°23'32,06" W) is in the Pre-puna phytogeographical region, at an altitude of 3000 m.a.s.l. It rests on an elevated plateau on the left bank of the Yacoraite River, a tributary of the Grande River in Humahuaca, Jujuy Province (Fig. 1, Table 3). It is a conglomerated village of roughly 10 ha. The site presents a complex internal structure of public spaces or squares, residential areas, a hierarchy of internal circulation routes and discard zones. The site was occupied during the first stage of the Regional Developments Period (or RDP I, ca. 900–1250 CE), but the greatest expansion was during the last phase of the Regional Developments Period (or RDP II, ca. 1250–1430 CE). At that time, the site became one of the largest settlements in the region. During the Inca Period (ca. 1430–1536 CE) the site was mostly abandoned, with only the central sector being occupied (Berardi, 2004; Nielsen, 2007). The sample analysed were obtained from excavations at different sectors within the site (Nielsen, 2007; Taboada and Angiorama, 2003). The general characteristics of these human remains – anthropogenic skull deformation, health and lifestyle indicators, burial and mortuary artefacts have been analysed by Seldes (2007, 2012). It is important to state, that the bioarchaeology revealed indicators of anaemia including porotic hyperostosis and *cribra orbitalia*. The high incidence of these stress indicators, among others, was associated with a maize-based diet,

Table 2
Isotope values and standard deviations of skeletal samples from de Antofagasta de la Sierra.

n	Procedence		Sample	Sex	Age range	AIE	$\delta^{13}\text{C}$ (± 0.2)	$\delta^{15}\text{N}$ (± 0.2)	C/N	AIE	$\delta^{13}\text{C}$ (± 0.1)	Chronology (BP)
	Site	Sub area										
1	El Aprendiz	Intermediate sectors	Rib	I	Adult	27,350	-10.9	10.5	3.3	28,710	-6.6	1828 \pm 57 ^b
2	La Alumbreira	Basis bottom	Rib	I	Adult	27,349	-14.4	10.1	3.3	28,775	-10.2	Late - Inca period
3	Casas Viejas	Basis bottom	Fibula	I	Adult	27,351	-14.9	9.7	3.5	28,700	-10.5	2000–1300
4	El Peinado	High ravines	Rib	I	Adult	27,508	-13.9	10.5	3.3	28,698	-9.5	Inca period
5	La Alumbreira ^a	Basis bottom	Bone	I	Adult	~	-13.9	10.5	~	~	-12.1	210 \pm 70
6	La Alumbreira ^a	Basis bottom	Bone	I	Adult	~	-13.2	11	~	~	-10.5	210 \pm 70
7	Bajo del Coypar II ^a	Basis bottom	Bone	I	Adult	~	-15.8	14.9	~	~	-11.7	1080 \pm 210
8	Qda. de la Cueva A2 ^a	Antofalla salt flat	Bone	F	24–34 years	~	-12.7	8.9	~	~	-11.6	1130 \pm 60
9	Qda. de las Cuevas A2 ^a	Antofalla salt flat	Bone	M	Adult	~	-13.1	9.6	~	~	-12.9	1180 \pm 60
					Mean		-14.0	10.7			-11.1	
					St. dev.		1.0	1.8			1.1	

^a Publish in Olivera and Yacobaccio, 1999.

^b AMS Arizona (ESCO-001); $\delta^{13}\text{C}$ - 11.4.

where the consumption of meat was deficient or low (Mercolli and Seldes, 2007)

3. Analytical methods

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ measurements (originally published in Killian Galván et al., 2016a, 2016b, 2016c) were carried out in the INGEIS Biogeochemistry Laboratory (CONICET-UBA). The procedure to extract bone collagen (Tykot, 2004; see also Killian Galván, 2015, for more details) consisted of two phases, demineralization and elimination of post-depositional particles. During the pre-treatment of the inorganic fraction we used Tykot's (2004) protocols, as well as those of Garvie-Lok et al. (2004). Measurements of each sample $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values were made on a Carlo Erba Elemental Analyser (CHONS), coupled to a Finnigan MAT Delta V continuous-flow isotope ratio mass spectrometer (CF-IRMS), through a Thermo ConFlo IV interface using internal standards. The analysis of carbon isotopic composition in carbonates was done using the phosphoric acid method developed by McCrea (1950), including later modifications (Panarello et al., 1980). The spectrometer used for hydroxyapatite samples was a Delta S Finnigan Mat triple collector (more details in Killian Galván, 2015).

3.1. Quantitative diet reconstruction

For the quantitative reconstruction of the ANS, RD and LA population diets we opted for the mixed Bayesian model FRUITS (Food Reconstruction Using Isotopic Transferred Signals), because it allowed us to estimate probability distributions of source contributions, it has user-friendly interfaces, and integrated complexities appropriate for paleo-diet reconstruction. The model allows us to handle different uncertainties, such as isotopic signals of potential food groups, diet-to-

tissue isotopic offsets and dietary routing (Fernandes, 2015; Fernandes et al., 2014). In this manner, we could begin to understand the relationship between the contribution of macronutrients and the dietary proxy signal measured in the consumer (Fernandes et al., 2014). On the other hand, FRUITS provides the possibility of introducing pre-existing information, for instance, from physiological or metabolic studies (Fernandes et al., 2014).

As with any other model, we should recognize its limitations and requirements. First, it must have a baseline definition of nutrient and isotopic composition of food groups. Second, it needs to use enough dietary proxies (up to three). Third, there must be a quantification of diet-to-tissue isotopic offsets and dietary routing. Fourth, the model is capable of handling uncertainties associated with all the parameters described above, while allowing the user to input diverse forms of pre-existing information (Fernandes, 2015). The average isotope values of the three dietary proxies ($\delta^{13}\text{C}_{\text{collagen}}$, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}_{\text{apatite}}$) of the ANS, RD and LA population are given together with an associated standard error of the mean (Table 1). Not all the individuals could be included in the model, because some of them do not have the three proxies (one case of RD has been excluded because it presented a great difference between $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{13}\text{C}_{\text{apatite}}$, probably due to contamination of the sample).

Three main food groups were considered: terrestrial C_3 plants, C_4 cereals, meat from terrestrial animals (basically camelids, as *Lama glama* [llama] and *Vicugna vicugna* [vicuña]), taking in account carbon and nitrogen isotopic composition of resources from previous studies (Table 4; Fernández and Panarello, 1999–2001; Gheggy and Williams, 2013; Killian Galván and Salminci, 2014; Killian Galván et al., 2015; Mengoni Goñalons, 2007; Otero, 2014; Samec et al., 2014; Yacobaccio et al., 2010). For the reconstruction of the RD diets, *Solanum tuberosum* represented the C_3 plants, while the C_4 and CAM set were considered

Table 3
In-site provenance, isotope values and standard deviations of skeletal samples from de Los Amarillos.

n	Procedence		Sample	Sex	Age range	AIE	$\delta^{13}\text{C}$ (± 0.2)	$\delta^{15}\text{N}$ (± 0.2)	C/N	AIE	$\delta^{13}\text{C}$ (± 0.1)	
1	Complex A		1° metatarsal (R)	I	Adulto	31,294	-11.2	10.0	3.2	33,230	-5.3	
2			1° metatarsal (R)	I	Adulto	31,295	-10.6	10.0	3.2	33,224	-5.2	
3	Complex B		Rib	F	Adulto	31,296	-11.6	11.3	3.2	33,231	-5.5	
4	Unit 400	Enclosure 402	Cista 2	Rib	I	Adulto	27,488	-10.1	10.3	3.2	28,771	-4.8
5			Rib	I	Adulto	27,477	-9.9	10.0	3.3	28,705	-4.2	
6			Rib	I	Adulto	27,494	-10.4	10.5	3.2	28,765	-4.6	
7			Rib	I	Adulto	27,495	-10.2	9.4	3.2	28,768	-4.8	
8			Rib	I	Adulto	27,492	-9.6	10.0	3.2	28,767	-3.9	
9	Complex E		Enclosure 301	Skull	I	Adulto	31,287	-10.5	11.9	3.4	33,236	-5.4
10			Enclosure 301	Skull	M	Adulto	31,288	-10.3	10.0	3.3	33,223	-5.0
11			Enclosure 303	Rib	F	Adulto	31,285	-10.6	10.3	3.3	33,233	-5.3
					Mean		-10.5	10.3			-4.9	
					St. dev.		0.5	0.7			0.5	

Table 4

Isotopic values per food resource assemblages. In the case of resources used at Río Doncellas the carbon isotope values do not show significant difference. In the case of nitrogen values there is overlap between the groups. Unexpectedly, the values were, in relation to the animal assemblage, even higher in C₄ plant resources. This also occurs for the Antofagasta de la Sierra assemblages, although here the highest nitrogen values occur in C₃ plant communities. The same occurs with Los Amarillos, although the differences between both groups are less.

Case studies	Resources	n	$\delta^{13}\text{C}$	\pm SD	n	$\delta^{15}\text{N}$	\pm SD
Río Doncellas (Jujuy)	C ₄ /CAM plants	11	-10.5	1	11	8.7	2.8
	Animals	115	-16.8	2.2	20	7.9	1.6
	C ₃ plants	24	-24.5	0.8	24	6.2	3.5
Archaeological sites from Antofagasta de la Sierra (Catamarca)	C ₄ plants	10	-10.1	1.5	8	4.9	3.3
	Animals	50	-17.4	1.7	50	6.2	1.2
Los Amarillos (Quebrada de Humahuaca, Jujuy)	C ₃ plants	11	-25.3	2	5	7.9	1.1
	C ₄ /CAM plants	37	-10.6	3.6	37	5.1	2.1
Los Amarillos (Quebrada de Humahuaca, Jujuy)	Animals	18	-16.1	2.8	18	6.3	2.7
	C ₃ plants	13	-24.9	0.9	13	6.9	1.5

respectively specimens of *Zea mays* and *Opuntia* sp. For the ANS case, the set of plants C₃ was composed of *Solanum tuberosum*, *Chenopodium quinoa*, *Geoffroea decorticans* and *Prosopis* sp., whereas the set C₄ was made-up only by *Zea mays*. Finally, for the LM case, the set of C₃ terrestrial plants was composed of *Solanum tuberosum*, *Chenopodium quinoa*, *Oxalis tuberosa*, *Manihot esculenta*, *Cucurbita moschata* and *Capsicum* sp., while for the C₄/CAM set *Zea mays*, *Amaranthus caudatus* and *Opuntia ficus-indica* were included. Their nutrient content (protein, carbohydrates and lipids) was expressed as dry weight carbon content (wtC %), with carbohydrates and lipids combined into a single fraction. For the estimation of macronutrient composition of foods, we used the Supporting Information File 2 – Table 1 published in Fernandes (2015) (FAOSTAT 2009).

For the carbon and nitrogen isotopic composition of camelids from ANS, the work of Grant (2014) was used ($n = 50$; average isotopic values = $\delta^{13}\text{C} -17.4 \pm 1.7\text{‰}$ and $\delta^{15}\text{N} 6 \pm 1.2\text{‰}$). The dietary composition of these animals was not clear in previous research (Killian Galván et al., 2016b). Nevertheless, based on all the above, it was possible to arrive at an accurate isotopic signal for the area, as well as the adjusted isotopic signal for the environment.

The isotope values of terrestrial animals were estimated from bone-collagen values, relying on previously reported offsets between macronutrient and collagen isotopic values for these organisms (Fernandes, 2015). It is important to state that this offset was different from those that had been used in previous research (Killian Galván et al., 2016a; Killian Galván et al., 2016b; Killian Galván et al., 2016c). Chosen offsets for terrestrial animals were, $\delta^{13}\text{C}_{\text{protein-collagen}} - 2\text{‰}$, $\delta^{13}\text{C}_{\text{lipids-collagen}} - 8\text{‰}$, $\delta^{15}\text{N}_{\text{protein-collagen}} + 2\text{‰}$, with an uncertainty of 1‰. As $\delta^{13}\text{C}_{\text{apatite}}$ is a dietary proxy that signals the carbon of the dietary mix, the $\delta^{13}\text{C}$ signal of each food group was that of the bulk carbon. On the other hand, terrestrial animals $\delta^{13}\text{C}$ bulk values were estimated as a weighted mean (in accordance with nutrient composition) of lipid and protein $\delta^{13}\text{C}$ values. Modern plant values were adjusted for isotope Suess effect (+1.5‰; Craig, 1957), and bulk isotope plant values were adjusted for isotope offsets between bulk $\delta^{13}\text{C}$ values and protein (-2‰), and between bulk $\delta^{13}\text{C}$ values and carbohydrates (ca. +0.5‰) (Fernandes, 2015; Tieszen, 1991). Diet-to-collagen, and diet-to-apatite, $\delta^{13}\text{C}$ isotope offsets were based on Fernandes et al. (2012), an offset of $4.8 \pm 0.2\text{‰}$ for the former, and an offset of $10.1 \pm 0.2\text{‰}$ for the latter, with a conservative uncertainty (0.5‰) to account for the possible effect of body size (Passey et al., 2005). Also, collagen carbon was routed from $74 \pm 4\%$ dietary protein carbon, and the remaining 26% from carbohydrates and lipids (as showed by Fernandes et al., 2012).

For human $\delta^{15}\text{N}$ diet-to-collagen isotope offset a value of

Table 5

Estimates generated by FRUITS of the average calorie contribution of each food group (Food %) for the Río Doncellas, Antofagasta de la Sierra and Los Amarillos population.

Case studies	Recourses	Mean	\pm SD
Río Doncellas	C ₄ /CAM plants	18	7
	Animals	36	23
	C ₃ plants	46	19
Antofagasta de la Sierra	C ₄ /CAM plants	35	10
	Animals	36	22
	C ₃ plants	29	18
Los Amarillos	C ₄ /CAM plants	66	6
	Animals	18	11
	C ₃ plants	14	9

$5.5 \pm 0.5\text{‰}$ was used (Fernandes, 2015). Finally, based on existing studies we took the acceptable level of dietary protein intake (Fernandes et al., 2014; Otten et al., 2006), as between 5 and 45% of protein carbon contribution.

4. Results and discussion

4.1. The archaeological site of Río Doncellas

The average calorie contribution of each food group (Food %) for the population was ca. 46% for C₃ plants, 18% for C₄/CAM plants and 36% for terrestrial animals (Table 5, Fig. 2). In using this model, the interpretation of the data changed radically in respect to earlier studies, given that the presence of terrestrial animal meat in the diet was more important here than in other previous articles (Killian Galván et al., 2016b; Pérez and Killian Galván, 2011). Until this study, an underestimated resource was tubers, in this case, potatoes (*Solanum tuberosum*). In fact, they demonstrated a similar isotopic distribution to that of animals.

Therefore, considering that the new model did not underestimate the plant contribution, and there was no protein bias against that kind of resources, we expected that tubers and meat would compete as the most important food sources. This was the reason why there was more uncertainty concerning these two groups vis-à-vis C₄ plants, given that the isotopic signal was markedly different from that of the other groups, at least in the case of carbon. The reduced input of *Zea mays*, or other plants with the same photosynthetic pathway, such as amaranth, remains a strong possibility. In only two cases was there coincidence between the new and old model (Killian Galván et al., 2016b), nevertheless there was still an overlap concerning the consumption probabilities of these resources. In other words, although in general there was a greater affinity with C₃ vegetables, two of the cases considered had a meat intake that exceeded 60% (Fig. 3).

In Killian Galván et al. (2016b), we highlighted the full exploitation of camelids, suggesting that there was also consumption of bone marrow and fat. Among the individuals analysed, the $\delta^{13}\text{C}_{\text{ap}}$ values were more impoverished than the collagen values. This would be expected in an energy intake strategy that emphasised the consumption of animal lipids. However, under the Bayesian mixing model FRUITS, these values could also correspond to the consumption of *Solanum tuberosum*, which has equally low $\delta^{13}\text{C}$ values.

This underestimation in the protein input of animal resources is in part a consequence of the limits that the FRUITS Bayesian model can generate based on pre-existing information (in this case, acceptable level of dietary protein intake). In this manner, it is more realistic to expect a balanced diet of different resources than a diet based solely on animal protein, which can have negative health impacts. In the present-day, the inhabitants of these areas obtain, through different food sources, the vitamins and minerals that their local herding and agricultural diet does not provide in great abundance. Although these might be isotopically invisible, only periodically or inconstantly consumed, as

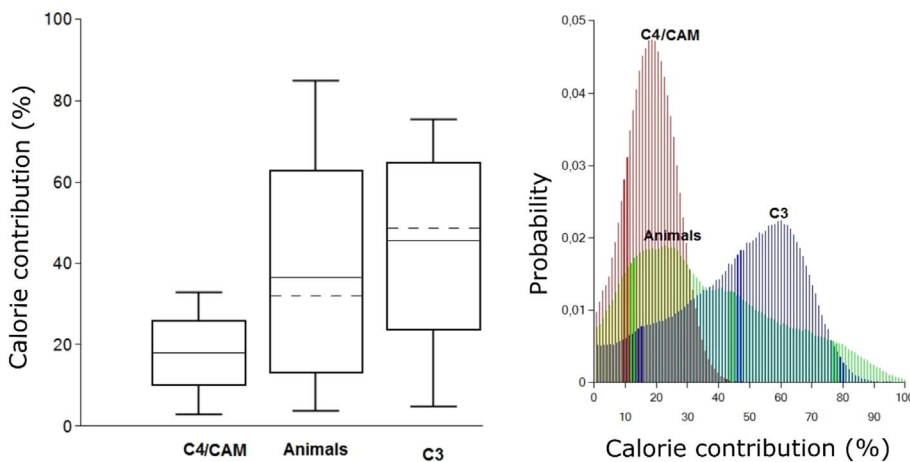


Fig. 2. Model estimates of calorie intake under for the isotope mean of the Río Doncellas individuals (credible intervals on the left and probability distributions on the right). Boxes represent a 68% credible interval (corresponding to the 16th and 84th percentiles) while the whiskers represent a 95% credible interval (corresponding to the 2.5th and 97.5th percentiles). The horizontal continuous line represents the estimated mean while the horizontal discontinuous line represents the estimated median (50th percentile).

well as in lesser quantity, these types of resources in the past would have guaranteed the local populations health within an environment often considered marginal.

On the other hand, our results show a slight predominance of cereal components in the diet of the individuals found in RD. Even though the number of individuals is still low, these results concur with the expectations of other scholars, such as Johnson et al. (2009). They established a threshold for maize production in relation to annual Effective Temperature. This temperature would have to be higher than 12.75 °C, in effect higher than the average for this sector of the Puna of Jujuy (~9.34 °C; Killian Galván, 2015). This underestimation of maize consumption is also consistent with studies performed on the skeletal assemblage's dental records analysed in this paper. Studies on the teeth revealed a low prevalence of caries, allowing us to infer that carbohydrates were not the main component of food. Neither did we find indicators associated with undernourishment (Miranda, 2010).

4.2. Archaeological sites from Antofagasta de la Sierra

The environmental constraints were similar as in previous case, but here maize was widely represented in the diets. The average calorie contribution of each food group (Food %) for the population was ca. 35% for C₄ plants, 36% for terrestrial animals, and 29% for C₃ (Table 5, Fig. 4).

When in previous articles the sample was analysed using a “protein diet” model (only information from collagen), the consumption of meat resources was highlighted and it was proposed that these meat resources had mostly fed on pastures with a C₄ photosynthetic signature (Killian Galván et al., 2016a). This led to the hypothesis that these animals were being fattened on a diet of maize and maize derivatives (husk, stalk, etc.), either as active foddering (Grant, 2014), or there was greater availability of pastures with this C₄ signature (Killian Galván

et al., 2016a). In support of this last hypothesis, a high C₄ signature was identified in the diet of camelids prior to the Late Holocene (Mondini et al., 2010), before the introduction of maize into the local economy. Nevertheless, the hypothesis citing the importance of C₄ plants to the diet was discarded once the camelidae sample was expanded.

Indeed, once we started analysing the diet in its totality, especially the data revealed through the analysis of stable isotopes of carbon in collagen and apatite (Killian Galván et al., 2016a), we realised that the main energy resources – expressed in lipids and carbohydrates – were predominantly C₃. This indicates that dietary energy was mainly garnered from cultivated resources such as tubers, quinoa, or gathered plants such as *chañar* (*Geoffroea decorticans*) and *algarrobo* (*Prosopis* sp.). Remains of these plants were found at archaeological sites in the area (Babot, 2009, Babot et al., 2009, among others). Maize, on the other hand, was hardly present. The exception in this scenario was an individual found at the Miriguaca area at the *El Aprendiz* archaeological site (Killian Galván et al., 2016a). This individual had the highest C₄ signature, and dates from the first millennia AD. Furthermore, individuals with a high C₄ content in their diet (e.g. the *Punta de la Peña 9* site) also date to ca. 500 CE. We noted then, that for this period agricultural intensification has been strongly suggested (Quesada, 2010), even though this micro-region has been interpreted as having benefitted from an expansion in farming, only later on at the start of the second millennium AD (Olivera and Vigliani, 2000–2002). This fact substantially changed our views of the resources available in the area (Killian Galván et al., 2016a). However, under FRUITS approach, in general, maize was identified as a keystone resource, and not only in the case of the possibly maize consuming individual found in the Miriguaca area (individual n° 1 in Fig. 5).

The inclusion of a greater number of local Camelidae isotopic values in this new approach allowed us the possibility of setting up a much more robust model. However, it was not possible to establish a clear

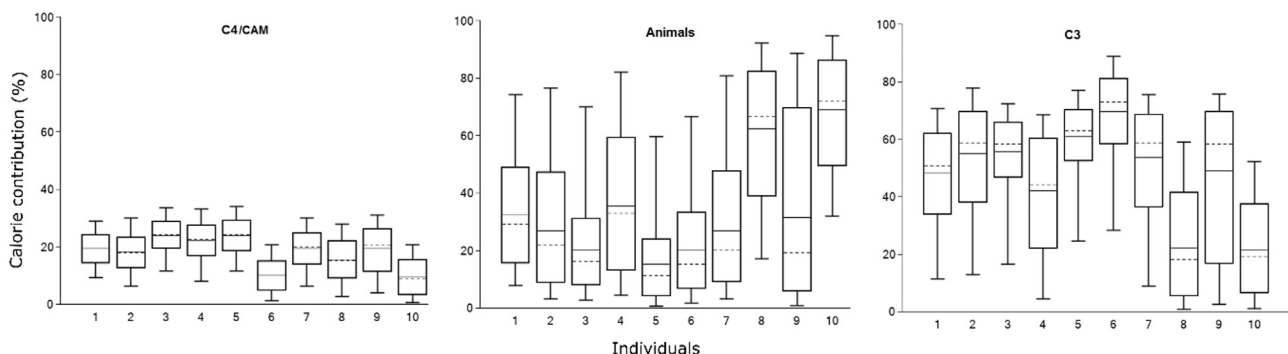


Fig. 3. Individual model estimates of calorie intake, expressed as credible intervals for Río Doncellas.

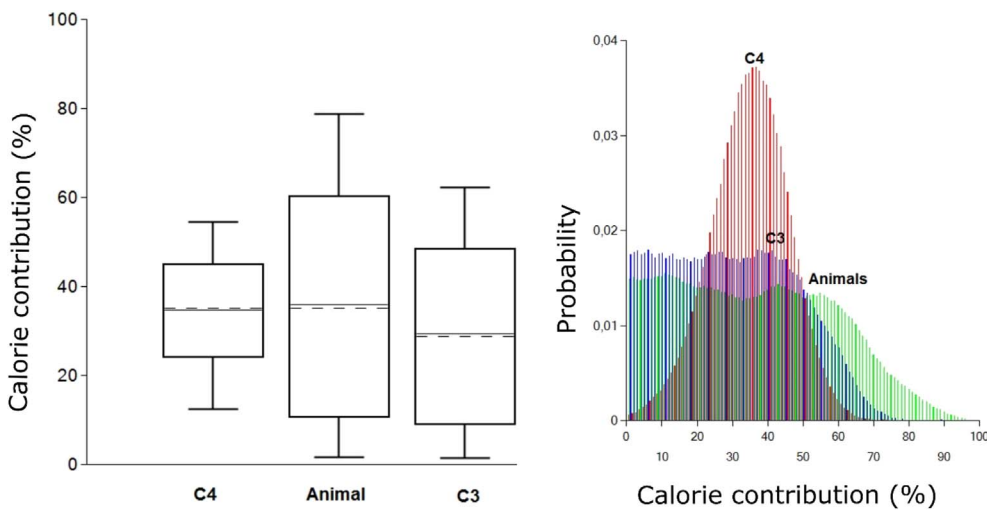


Fig. 4. Model estimates of calorie intake under for the isotope mean of the Antofagasta de la Sierra individuals.

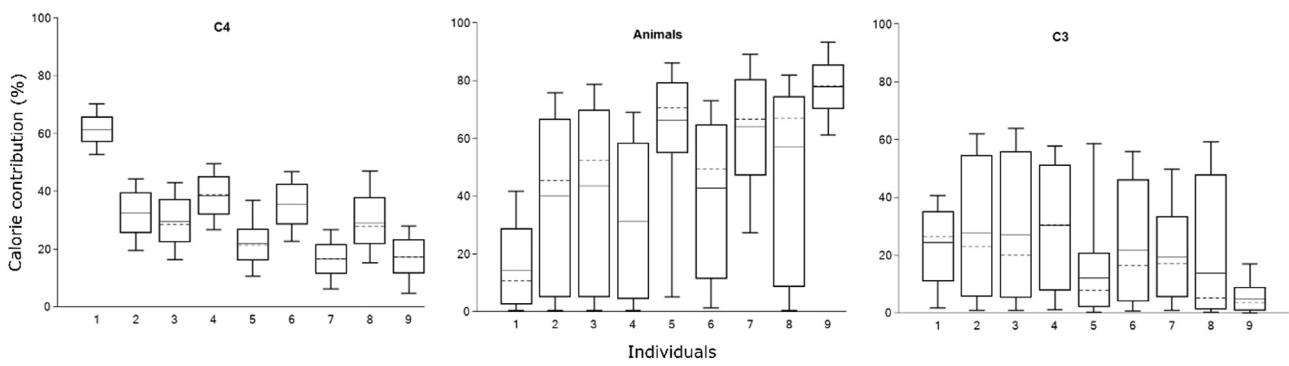


Fig. 5. Individual model estimates of calorie intake, expressed as credible intervals for Antofagasta de la Sierra.

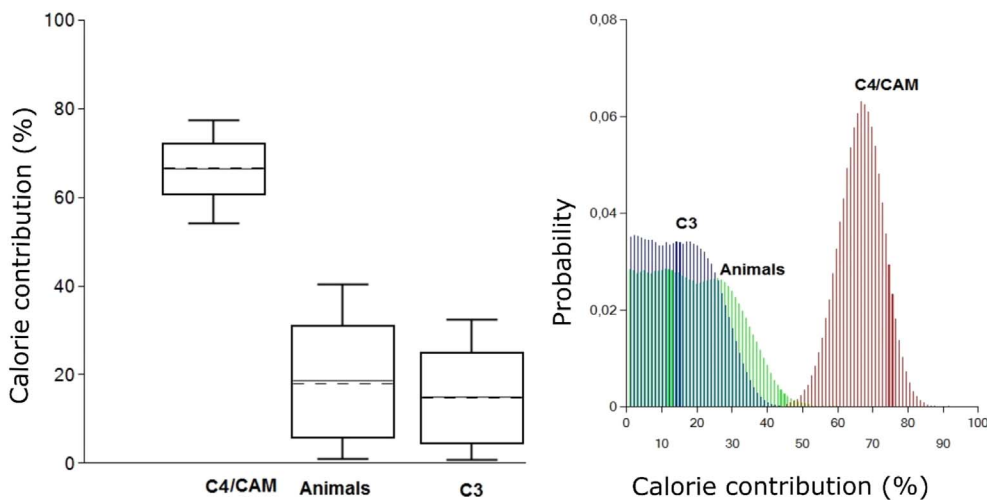


Fig. 6. Model estimates of calorie intake for the isotope mean of the Los Amarillos individuals.

hierarchy between resources, given the difficulties we found differentiating between the most important resources, and the fact that they all had similar isotopic signals. Indeed, the high level of uncertainty in our model made it very difficult to determine the importance of camelids in the local diet. This has been one of the problems we had aimed to address in our use of FRUITS.

4.3. Los Amarillos (Quebrada de Humahuaca)

The average calorie contribution of each food group (Food %) for the population was ca. 66% for C₄/CAM plants; 18% for terrestrial

animals, and 14% for C₃ plants (Table 5; Figs. 6 and 7).

Previous interpretations of the data (Killian Galván et al., 2016c) had emphasised the importance of *Zea mays* in the diet (although the presence of amaranth could not be completely discounted). In those interpretations, the consumption of meat (and tubers) was deemed to be minor (Killian Galván et al., 2016c). However, in a similar fashion to the case above though, previous studies had not integrated the three strands of isotopic evidence ($\delta^{13}\text{C}_{\text{collagen}}$, $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{15}\text{N}$) simultaneously, and therefore faunal resources were over-represented within the paleodiet (Killian Galván et al., 2016c). When we estimated the “protein diet”, animal resources, especially those with a high C₄

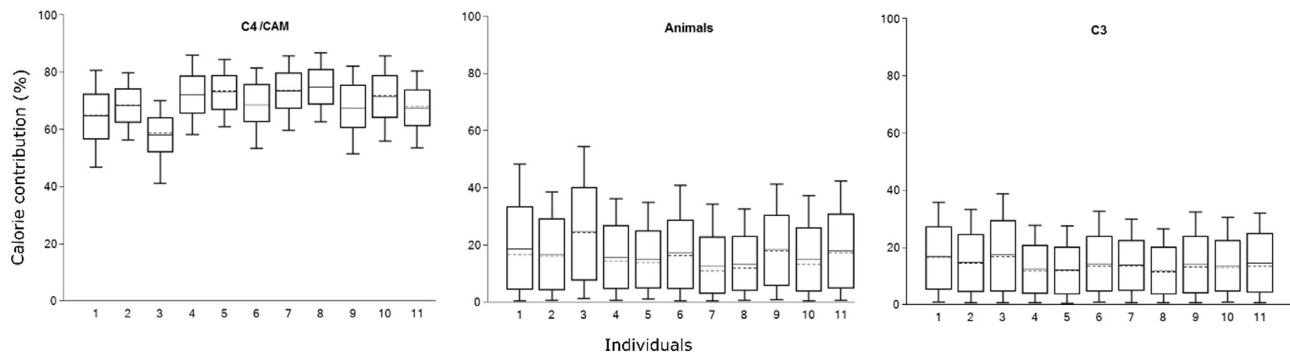


Fig. 7. Individual model estimates of calorie intake, expressed as credible intervals for Los Amarillos.

signature seemed to enjoy equal importance to plant resources with a C₄ (maize and amaranth), and CAM (cacti) signature. In turn, this implied that there was an equal integration of both types of resources (Killian Galván et al., 2016c). This could have come about due to a larger availability of C₄ pastures for these animals, or a deliberate strategy of fattening on maize, and derivatives for the same. This might have been common practice in Quebrada de Humahuaca, leading to a strategy of intensification and exploitation of agricultural products and by-products (Killian Galván et al., 2016c).

Nevertheless, when we consider only the local isotope data of *Lama glama* under the mixed FRUITS model, we observe that the ranking of meat resources falls in respect to other foodstuffs. It is important to note that the paleodietary estimate undertaken using this model was coherent with the state of health inferred from bioarchaeology for the skeletal assemblage of the Los Amarillos site. At this site, the bioarchaeology revealed anaemia indicators due to a lack of iron, leading to porotic hyperostosis and *cribra orbitalia*. The high incidence of these stress indicators, among others, was associated with a maize-based diet, where the consumption of meat was deficient or low (Mercolli and Seldes, 2007). Furthermore, porotic hyperostosis was much more prevalent than *cribra orbitalia*, with the latter only appearing on a few individuals. Following Walker et al. (2009), it is possible that these indicators do not have one single cause (i.e. lack of meat in the diet) given that porotic hyperostosis is associated to megaloblastic anaemia due to a vitamin B12 deficiency. B12 is mainly found in animal products. *Cribra orbitalia* is associated to a lack of vitamin C, which can be obtained through the consumption of fresh fruit and other sources. The relative importance of maize (and/or amaranth) inferred from the FRUITS model was therefore coherent with this interpretation, including, as it did, the low importance that meat products had. Indeed, meat was of secondary importance within the general diet.

5. Conclusions

In this article, we presented three case-studies that assessed existing and new interpretative models towards the qualitative and quantitative paleodietary reconstruction. The need to reach more robust interpretations feeds into recent discussions concerning the Prehispanic economy of North-western Argentina (Killian Galván, 2016). In this respect, climatic variations, and its impact on the growth season in this macro-region influenced the relative importance of plant and animal resources on human consumption. For instance, while at RD and ANS a pastoralist intensification led to a higher dietary intake of animal resources, in the Quebrada de Humahuaca – where the site of LA is located – higher temperatures led to a longer growth season, which resulted in more agriculture, and an increase in maize within the local diet (Killian Galván, 2016). Furthermore, the interpretation of the isotope data using the FRUITS Bayesian model integrates both previous data and analyses macronutrient concentrations, observing how the latter influences the isotope signature. In this manner, we achieved a

more realistic model of consumption than those that used a qualitative focus (Killian Galván et al., 2016a, 2016b, 2016c). In the case of RD, it led us to infer the importance of tubers in the diet. These tubers could well have been cultivated in the large areas of terraces that are located near to the site. Similarly, the underestimation of animal products in the diet, a flaw in earlier interpretations (Killian Galván et al., 2016b) permitted us to propose an interpretative framework that was more in-keeping with what we would expect of a healthy diet. Likewise, it made it possible to better tie the existing isotopic and bioarchaeological evidence from Los Amarillos.

Nevertheless, even if our new focus has been shown to be useful in estimating the importance of plants in respect to animals in the diet, this can only be done if there is a clear difference between the isotope values of both resources. Given that, as we can see in this article, when overlap occurs, the values display large error margins leading to uncertainty in the relative ranking of resources consumed. This is the case of Antofagasta de la Sierra, in which we need to generate further local isotope values, thereby limiting the isotopic range of each of these resources. The need for this is equal to, or more important, than the selection of which analytical models to employ from hereon in.

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