Camelid husbandry in the Atacama Desert? A stable isotope study of camelid bone collagen and textiles from the Lluta and Camarones Valleys, northern Chile

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Abstract

Management of camelids in the coastal valleys of the Andes has generated much debate in recent years. Zooarchaeological and isotopic studies have demonstrated that in the coastal valleys of northern and southern Peru there were locally maintained camelid herds. Because of the hyperarid conditions of the northern coast of Chile, this region has been assumed to be unsuitable for the raising of camelids. In this study we report stable carbon and nitrogen isotopic compositions of camelid bone collagen and textiles made from camelid fiber from Late Intermediate Period (LIP) and Late Horizon (LH) occupations in northern Chilean river valleys. The camelid bone collagen isotopic compositions are consistent with these animals originating in the highlands, although there is a significant difference in the camelids dating to the LIP and LH, possibly because of changes made to distribution and exchange networks by the Inca in the LH. There were no differences between the isotopic compositions of the camelid fibers sampled from textiles in the LIP and LH, suggesting that either the production of camelid fiber was unchanged by the Inca or the changes that were made do not present visible isotopic evidence. Several camelid fiber samples from both the LIP and LH present very high δ¹³C and δ¹⁵N values, comparable to human hair samples from one site (Huancarane) in the Camarones Valley. These data suggest that people in the northern valleys of Chile may have kept small numbers of animals specifically for fiber production. Overall, however, the vast majority of the textile samples have isotopic compositions that are consistent with an origin in the highlands. These data suggest that the hyperarid coastal river valleys of northern Chile did not support substantial camelid herds as has been interpreted for northern Peru.

Introduction

Camelids (llama [Lama glama] and alpaca [Vicugna pacos]) were the only species of large animal to be domesticated in the Americas. Although they were not used for milk and traction,
they were used extensively for their meat [1–3] and leather [4, 5], as beasts of burden in caravans [6, 7], and their dung was used for fertilizer and fuel [5, 8, 9]. Their most important economic role, however, was the production of fiber to be used to manufacture textiles. These textiles were of tremendous economic, social, and political importance throughout the Andean region [10, 11]. The Inca extracted labor taxes of rough cloth from households and also utilized fine cloth woven by high status, specialist weavers [12–14]. Under Inca control during the Late Horizon the mit'a was an institutionalized labor service through which conquered peoples paid tribute, providing an important source of income for the state [13, 15]. The mit'a consisted of a rotational labor system, including herding camelids, farming, and weaving, among other activities. The textile mit'a was one of the most important, since clothing was the object most valued by the Inca state in economic, political, and ritual terms [11, 13]. In the textile mit'a the state provided high quality fiber which was spun and woven into fine cloth, while women might have supplied their own tools [16].

Because textiles worn as clothing were highly visible, they were important embodiments of social identity, status, and power [17–19]. The way that scholars have thought about the role of camelids in Andean societies is strongly influenced by ethnographic and ethnohistoric descriptions, particularly those associated with the Inca. Based on these data, camelids have been seen as animals that reside in the high altitude grasslands of the altiplano (above 3,800 masl) and their presence in archaeological deposits outside of this narrow altitudinal range is sometimes assumed a priori to represent the presence of meat (dried as charqui) or fiber that was acquired via exchange with the highlands. Based on an extensive synthesis, Bonavia [20] concluded that there is little empirical evidence to support the notion that camelids are high altitude specialists, tracing the origins of this back to a statement made by Troll [21]. Bonavia [20] suggests that the natural habitat of the camelids “extends from sea level to altitudes over 5,000 masl, from the coastal deserts and fertile intermontane valleys to the high punas and the exuberant wet region of the ceja de selva, with all of the intermediate life zones that are far more varied than usually thought” (see also [22]).

Mounting isotopic evidence from the north coast of Peru has demonstrated the presence of local camelid populations in these areas from at least the Early Intermediate Period (c. 200 BC) [23–28]. Moreover, isotopic data demonstrate that camelids (probably llamas) were raised in an urban environment at the Wari site of Conchopata and intensively foddered with maize (>75% of the diet [29]). Shimada and Shimada [30] summarized other lines of evidence, which are also consistent with the raising of camelids on the north coast of Peru since at least the Middle Horizon (c. AD 600). Isotopic data indicate that meat and fiber was derived from local animals [26, 31, 32]. This finding runs counter to the widely-held assumption that the fiber in textiles found at low elevation sites must have originated in the highlands [19, 33], although in some cases (i.e., Chancay, central Peruvian coast, Late Intermediate Period) the fiber was exclusively imported from the highlands [31]. Nevertheless, these data are consistent with Bonavia’s conceptualization of camelids as highly adaptable to a wide variety of environments. What is still unclear, however, is just how widespread the occurrence of non-highland camelid husbandry was in the Andean region. The fact that these animals could survive in a given environment does not mean that they did.

The purpose of this study was to investigate if the inhabitants of two of the northern valleys of Chile (Lluta and Camarones) maintained local populations of camelids during the Late Intermediate Period and Late Horizon. Isotopic compositions of camelid skeletal remains suggest that these individuals most likely lived in the altiplano, although there were significant differences in the isotopic compositions of the LIP and LH camelid samples. The majority of fiber samples from textiles recovered from both LIP and LH contexts also originated in the

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altiplano, but a small percentage of the fibers from both periods were most likely derived from local animals, raised under very arid conditions at lower altitudes.

Setting and archaeological context

The environment of our study area is one that is, in many ways, intermediate between southern Peru to the north and the central Atacama Desert to the south. The study area is located in the northern section of the Atacama Desert between 18° and 19°S [34]. Unlike the coast, which offers abundant and stable marine resources, the inland valleys of the northern Atacama Desert are comparatively unstable places for human occupation, due to low biological productivity, limited availability of fresh water, periodic droughts, and overall lower predictability of resources [35].

The Lluta and Camarones rivers originate in the highlands (Lluta at 3,900 masl and Camarones at 2,900 masl), draining into the Pacific Ocean. They are the only rivers in northernmost Chile that present permanent runoff throughout the year, but occasional prolonged droughts may cause their runoff to terminate in their lower courses [36]. These rivers are characterized by extremely high concentrations of metals (As, B, Cu, Li, Na, K) [37], which limits the quantity and quality of wild vegetation, restricting it to the riverbed and areas fed by spring water. In fact, the sites under study are strategically located in association with fresh water springs. The limited vegetation coverage and the quantity and quality of water available in the Lluta and Camarones valleys make them unsuitable for supporting large numbers of animals, both wild and domesticated. Pre-Hispanic populations inhabiting these valleys had access to a limited variety of plants, seeds, and fruits. Agriculture generated important complementary resources, although also limited in variety (possibly only maize in pre-Hispanic times).

According to regional paleoclimate records, since 3,000 BP the current hyper-arid conditions have predominated in the Atacama Desert, although there were significant increases in rainfall at various intervals including 1050–600 cal. BP – the Medieval Climatic Anomaly (MCA), which roughly coincides with the Late Intermediate Period and Late Horizon [38–40]. Although climatic conditions were similar to those at present, these rainy events would have been more frequent during the MCA and would have meant a recharge of the fluvial and spring water resources. It is presumed, therefore, that there was greater vegetation coverage and more water available during the periods under study than there is presently.

The Late Intermediate Period and Late Horizon witnessed the development of the Arica Culture as a group of segmented societies that shared a common cultural tradition, although they did not comprise a single political entity. These communities practiced a mixed agro-maritime subsistence and had differential settlement and architectural patterns, as well as interactions with other groups [41–43]. During the Late Horizon, the impact of the Inca in the region is demonstrated by multiple lines of evidence, including typical Inca-style goods, as well as other proxies for changes in local economic activities, settlement patterns, and health conditions [44–46].

The samples analyzed in this study are from five small villages: four from the Lluta Valley (Rosario 2 [LL36], Sora Sur [LL19], Poblado Millune [LL21], and Vinto 1–2 [LL93]), and one from the Camarones Valley (Poblado Huancarane 1) (Fig 1). LL36 was excavated in 1995 by Calogero Santoro [47]. LL19, LL21, and LL93 were excavated in 2011–2012 [48]. Huancarane was excavated in 1978 by Niemeyer and Schiappacasse and its collection was studied in 2015 at the Museo Nacional de Historia Natural (Santiago de Chile). Radiocarbon dates for these sites are summarized in Table 1. All dates listed in Table 1 were calibrated in Calib v7.0.4 [49] using SHCal13 [50].
The archaeological site LL-36 (Rosario 2) is a hamlet located 16 km from the Pacific coast, composed of *totora* (reed) walled rectangular structures raised on artificial platforms reinforced with frontal stone walls, to level the steep slope of the valley [43]. Based on stratigraphy, radiocarbon dating, and ceramic components, it has been estimated that the earliest...
occupation was brief, corresponding to the Late Intermediate Period. More intense occupation occurred during the subsequent Late Horizon, as the inhabited surface of the site became larger, and midden deposits are more dense. The site is also distinguished by the occurrence of typical Inca goods (mainly ceramics, such as Inca Polychrome and Saxamar or Inca-Pacaje types, and some fragments of *khipu*) and a large number of exotic goods. Domestic remains show consumption of a wide array of marine resources (e.g., mollusks, fish, seaweed, sea stars), terrestrial fauna (e.g., camels, guinea pigs), wild plants (e.g., molle, *totora*), crops (e.g., cotton, pumpkin, bean, *ch’uño*, and corn), mineral copper beads, basketry, weaving tools, and abundant textile remains. Systematic analysis of ceramics indicates important changes related to the Inca influence [46, 47, 49].

LL-19 (Sora Sur), located 48 km from the Pacific coast, is a small village of circular precincts made of stones [48]. An occupation from the Late Intermediate Period and another from the Late Horizon were found during excavation. Generally, there are no significant differences between the material culture and biological remains from these two periods, which consist of wild plant remains (e.g., *Schinus molle*, *Prosopis* sp.), crops (*Lagenaria* sp. and *Zea mays*), and lithic artifacts. Camelids and other terrestrial fauna such as canids and rodents (e.g., *Chaetophractus nationi*, *Chinchilla* sp., *Cricetidae*) are scarce. Marine fauna is also represented by a small number of mollusks (*Choromytilus chorus*, *Littorina peruviana*, *Mytiloides*), *Perumytilus purpuratus*) and unidentified fish. Some textiles (mainly yarns) were also recovered. Local (e.g., Pocoma, San Miguel, and Gentilar) and highland (e.g., Black on Red and Charcollo) pottery types occur in both strata, with Inca Imperial ceramics limited to the Late Horizon stratum.

LL-21 (Poblado Millune, 54 km from the Pacific coast) is a complex village of circular precincts made of stones, organized in differentiated sectors: habitation, storage, and funerary [48]. The excavated deposit contained an occupation that was assigned to the Late Horizon. The materials recovered include local (e.g., San Miguel), highland (e.g., Chilpe, Charcollo), and Inca Imperial pottery, lithic and plant artifacts, and textiles (mainly yarns). There is a predominance of plant remains, with both wild (e.g., *Prosopis* sp., *Schinus molle*, *Equisetum* sp., *Typha angustifolia*) and domesticated (e.g., *Cucurbita* sp., *Gossypium* sp., *Lagenaria* sp., *Zea mays*) species represented. Faunal remains are relatively scarce, with the assemblage consisting of terrestrial mammals (e.g., Camelidae, *Lama* sp., *Lycalopex* sp., *Chinchillidae*), mollusks (e.g., *Choromytilus chorus*, *Perumytilus purpuratus*), and finfish (*Trachurus murphyi*).

LL-93 (Vinto 1–2, 57 km from the Pacific coast) is a hamlet composed of residential, funerary, storage, and public use structures (*kancha*, i.e., enclosure) [48]. Three occupations were identified, dating to: the Late Intermediate Period, Late Horizon, and Colonial Hispano-Indigenous Period. The material culture throughout these periods does not show significant changes in composition and consists of lithic artifacts, and mollusk and plant tools. Ecofacts include gathered plant remains (e.g., *Prosopis* sp., *Phragmites australis*, *Schinus molle*, *Tessaria abdinthioides*, *Equisetum* sp., *Scirpus* sp., *Typha angustifolia*, *Tessaria abdinthioides*), crops (*Cucurbita* sp., *Gossypium* sp., *Zea mays*, *Capsicum* sp.), camelids (*Camelidae*, *Lama* sp., *Vicugna* sp.), rodents (*Cavia* sp., *Caviomorpho*, *Chinchillidae*, *Cricetidae*, *Lagidium* sp.), and other unidentified mammals. Coastal resource procurement is evidenced by the presence of mollusks (*Choromytilus chorus*, *Scurria scurra*, *Tegula* spp). Some textiles (mainly yarns) were also recovered. The ceramics include highland types (e.g. Charcollo) and, in late periods, Inca Imperial styles. The colonial occupation of the site was documented by the presence of skeletal remains of Old World taxa and Hispanic pottery.

Huancarane 1 (60 km from the Pacific coast) is a village composed of stone structures, with differentiated areas (habitation, storages, and funerary) architecturally similar to the Lluta
villages described above [48]. The archaeological material comes from the excavation of habitation and storage structures, although stratigraphic information is lacking. The evidence recovered from the excavations includes cultivated (Zea mays, Phaseolus sp., Lagenaria sp., Gossypium sp.), and wild plant remains (Prosopis sp.), lithic artifacts, wood, and textiles [52]. Some fiber samples were microscopically analyzed and identified as llama, guanaco, and vizcacha (Lagidium sp.) by Niemeyer and Schiappacasse [52]. The pottery includes LIP Pica-Tarapacá, Arica, Altiplano and Inca components [53]. Marine mollusks (Choromytilus chorus, Oliva peruviana, Cryphiops caementarius) and freshwater crustaceans (Cryphiops caementarius) were recorded, but both were scarce. On the contrary, abundant remains of terrestrial fauna were recovered, including camelids, rodents (Chinchilla sp), and other unidentified mammals.

**Isotopic context**

The application of isotopic analysis in the study of animal husbandry and the trade in animal products is a rapidly growing area of inquiry. Some isotope systems, such as hydrogen, oxygen, strontium, and lead, record the location in which an animal lived [54], and these techniques have been applied with some regularity in archaeological contexts to address the trade in animal products [55–59]. Stable carbon and nitrogen isotope compositions are not tied to geography in the same way as these other isotope systems, but in certain regions where environmental variation is large over relatively small spatial scales or particular feeding practices that are isotopically unique exist, carbon and nitrogen isotopes can be an effective means of assessing the locality of animals and animal products in the archaeological record [31, 32, 60].

The carbon and nitrogen isotope compositions of a consumer’s tissues reflect the average carbon and nitrogen isotope compositions of the foods consumed during the period of tissue formation [61, 62]. The carbon in bone collagen is predominantly routed from dietary protein [63, 64]. Herbivore tissue $\delta^{13}C$ and $\delta^{15}N$ therefore reflect the $\delta^{13}C$ and $\delta^{15}N$ of the plants that they consumed [65, 66], which are in turn sensitive to a number of environmental parameters [67, 68].

Photosynthetic pathway is the primary mechanism influencing the $\delta^{13}C$ values of plants. Excluding plants growing under dense forest canopy, $C_3$ plants have $\delta^{13}C$ values that range between $\sim 35$ and $\sim 20$‰ with a mean of $\sim 27$‰; $C_4$ plants (predominantly tropical grasses) have $\delta^{13}C$ values that range between $\sim 15$ and $\sim 7$‰ with a mean of $\sim 12$‰; CAM plants (cacti, succulents, and epiphytes) have $\delta^{13}C$ values that range between $\sim 22$ and $\sim 10$‰ [69–71]. $C_3$ plant $\delta^{13}C$ values are sensitive to environmental variation through influences on the ratio of ambient to intercellular partial pressure of CO$_2$ [67, 72]. The $\delta^{13}C$ values of $C_3$ plants are correlated with water availability such that plants growing in arid conditions have higher $\delta^{13}C$ values than those growing in wetter conditions [73–76]. Water availability does not appear to influence $C_4$ plant $\delta^{13}C$ [75, 77], which are generally less sensitive to environmental variation and exhibit a much narrower range of $\delta^{13}C$ values than $C_3$ plants [72]. The entire region considered for this study is characterized by low water availability, therefore, wild $C_3$ plants will have $\delta^{13}C$ values that are higher than the global average. In a series of altitudinal transects between 22°S and 25°S in northern Chile, Quade et al. [78] found the average $\delta^{13}C$ of $C_3$ plants to be $\sim 23.1$‰ (c. $\sim 21.6$‰ after accounting for the Suess Effect). Similarly, Rundel et al. [79] found the average $\delta^{13}C$ of $C_3$ plants growing in the pre-puna shrubland zone (c. 3,550 masl) at 18°S to be $\sim 24.1$‰ (c. $\sim 22.8$‰ after accounting for the Suess Effect). The $\delta^{13}C$ of the overall biomass at high altitudes (>3,500 masl) is still lower than at low altitudes because of the rarity of $C_3$ plants [80, 81]. Despite the rarity of $C_4$ plants in the arid highland regions of northern Chile, the $\delta^{13}C$ values of herbivores consuming pure $C_3$-diets should be relatively high. In In
this region, herbivore $\delta^{13}C$ values of $-18\%$ do not necessarily imply the consumption of any C$_4$ plants assuming a consumer-diet trophic enrichment factor ($\Delta^{13}C$) of c. $+5\%$ [82]. Soil salinity also influences the $\delta^{13}C$ values of plants, with high values occurring with increasing soil salinity [83–85]. Finally, plants growing under dense forest canopies have lower $\delta^{13}C$ values than plants growing in open habitats [86–88], although this particular variable is not relevant for this study as the area lacks the necessary tree cover.

Plant tissue $\delta^{15}N$ values are determined primarily by the N source [68], the most important of which are mineralized N (NO$_3^-$ and NH$_4^+$) and atmospheric N$_2$ [89, 90]. Some plants in environments with low mineralization rates (typically boreal and arctic environments) also rely to a significant extent on organic N [91]. There is essentially no discrimination against $^{15}N$ during the conversion of N$_2$ to NH$_3$, a process that is known as biological nitrogen fixation (BNF [92, 93]). Plants that have the capacity to rely on N$_2$ through symbiotic associations with bacteria (primarily legumes, Fabaceae) therefore tend to have $\delta^{15}N$ close to that of atmospheric N$_2$ [94–96], which is 0\% [97]. The reliance on N provided through these symbiotic associations is, however, metabolically expensive and if soil N availability is high, legumes and other taxa capable of BNF will rely on mineralized N sources [94].

The types of mycorrhizal associations that plants form are also an important factor in influencing plant $\delta^{15}N$, with plant values being highest in non-mycorrhizal and arbuscular mycorrhizal (AM) plants, lower in ectomycorrhizal (EcM) plants, and lowest in ericoid (ErM) mycorrhizal plants [98, 99]. Generally there is latitudinal variation in the distribution of mycorrhizal types, following trends in temperature and soil N mineralization rates, with AM plants dominating in temperate grasslands and savannahs, EcM plants dominating in temperate forests and boreal taiga, and ErM dominating in high latitude tundra [100, 101]. Altitudinal trends in mycorrhizal associations are less well studied, but it appears that AM abundance declines with altitude, EcM abundance peaks at mid altitudes (1,000 to 2,500 masl), and the abundance of ErM is generally limited by the distribution of their plant partners, the Ericaceae, which tend to occur in acidic soils with low N availability [102].

In agricultural systems, additional N may be added to the soil through fertilization. The use of N derived from fertilizers has the capacity to increase plant $\delta^{15}N$ values by a few % for manure derived from domestic herbivores such as cattle or camelds [103–105] to greater than 20 \% for seabird guano [94, 105, 106]. Both types of fertilizer would have been potentially available in the study area and in fact the only convincing evidence of the prehistoric use of seabird guano as a fertilizer to date comes from the Atacama Desert immediately south of our study area [107].

Plant $\delta^{15}N$ tends to be positively correlated with temperature [108, 109] and negatively correlated with water availability [65, 74, 75, 98, 108, 110]. Because average temperature decreases and annual precipitation increases moving from the Pacific coast and into the highlands of Peru and Chile, plants growing at high altitudes have lower $\delta^{15}N$ than those growing at lower altitudes [111]. That said, the high altitude puna of northern Chile is distinct from that which exists in Peru in that it is far more arid. This region does receive more precipitation than the coast, but the region is still arid, with the northern Chilean dry puna receiving 300–350 mm of annual precipitation [112]. Despite the aridity of the puna, studies conducted in the hyperarid salt puna around 23.5°S [113] and in the Argentine dry puna [114] found plant $\delta^{15}N$ values to be comparable to those observed in the highlands of northern Peru (c. +2 to +6 \%o) [111]. Given that herbivores tissue $\delta^{15}N$ values are 3 to 4 \% higher than the plants that they consume [115], we would expect camelds that lived in the puna to have tissue $\delta^{15}N$ values between +5 and +9 \%o. This expectation requires testing through the collection of isotopic data from archaeological camelids recovered from sites in the highlands of northern Chile. For animals living in the low altitude coastal river valleys of northern Chile we expect much higher $\delta^{13}C$
and δ¹⁵N values than those living in the highlands driven primarily by the influence of aridity on plant δ¹⁵N values and the greater abundance of C₄ plants, particularly cultivated maize, which could have been used as fodder for camelids.

**Materials and methods**

**Sample preparation**

Bone collagen was extracted by demineralizing chunks of bone (c. 200 mg) in 0.5 M HCl at room temperature under constant motion (orbital shaker) for 7 days with periodic changing of the acid solution. After demineralization, the samples were rinsed to neutrality with Type I water and then those samples that were darkly colored were treated with 0.1 M NaOH for 20 min under constant motion (orbital shaker). If after 20 min the solution changed color, the solution was removed and fresh NaOH solution was added. Once there was no color change in the solution after 20 min, the samples were rinsed to neutrality with Type I water. The samples were then heated at 75°C for 36 h in 4 ml of 10⁻³ M HCl. After heating the solution containing the water-soluble collagen was transferred to a vial and freeze-dried.

The textile samples were cleaned of any visible particulate matter with a dental pick. The samples were then sonicated in Type I water for 60 min, centrifuged and air-dried. The textiles samples were then sonicated in 2:1 chloroform-methanol (v/v) for 60 min, centrifuged and air-dried.

**Isotope ratio mass spectrometry**

Carbon and nitrogen isotopic and elemental compositions were determined using a Nu Horizon continuous flow isotope ratio mass spectrometer couple to a EuroEA 3000 elemental analyzer at Trent University. Sample isotopic compositions were calibrated relative to VPDB (δ¹³C) and AIR (δ¹⁵N) using USGS40 and USGS41a or USGS66 [116–118] (S1 Appendix). Elemental compositions were calibrated using USGS40. Analytical uncertainty was assessed using four internal standards interspersed among the samples and 20% of the samples were analyzed in duplicate (S1 Appendix). Standard uncertainty was determined to be ±0.20 ‰ for δ¹³C and ±0.29 ‰ for δ¹⁵N [119].

**Sample integrity**

Quality criteria are not as well established for ancient keratin as they are for collagen. Boudin et al. [120] found an atomic C:N ratio range of 3.4–3.8 to be reliable within the context of ¹⁴C dating of wool. von Holstein et al. [121] found minimal changes to the carbon and nitrogen isotope compositions of wool textiles undergoing experimental degradation. Our approach to monitor for textile samples with unreliable isotopic compositions altered by post-depositional processes was informed by the approaches of Ambrose [122] and DeNiro [123] for bone collagen. DeNiro defined an acceptable range of 2.9–3.6 for unaltered collagen by examining the elemental and isotopic compositions for different taxa and noting that the collagen samples with C:N ratios outside the range of 2.9–3.6 tended to produce isotopic compositions that were too high or too low (S1 Appendix). Subsequently, others have discussed other quality control measures [122, 124–126], but DeNiro’s range of 2.9–3.6 for atomic C:N ratios remains the most frequently cited quality control measure in isotopic studies of ancient collagen [119]. We have taken a similar approach to DeNiro and compared the isotopic compositions and the atomic C:N ratios of the textiles analyzed in this study, as well as several others from the Andean region (Fig 2).
Fig 2. Relationship between isotopic and elemental composition of camelid fiber textiles. Carbon and nitrogen isotopic compositions of textiles analyzed in this study, as well as other camelid fiber samples from previously published papers \[26, 31, 32\]. Samples are colored according to their atomic C:N ratio.

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The data produced by DeNiro for bone collagen show clear differences in isotopic compositions between samples with C:N ratios within vs. outside of the 2.9–3.6 range (S1 Appendix). Specifically, the $\delta^{13}C$ values tend to be especially low when the C:N ratios are outside of the 2.9–3.6 range and the $\delta^{15}N$ values are much more variable (may be too high or too low). For archaeological camelid fiber, the samples with relatively high and low C:N ratios were not distinct, unlike those presented for DeNiro’s bone collagen data. This difference may be because highly degraded keratin does not survive in the burial environment while bones containing virtually no residual organic matter are reasonably common.

Although Boudin et al. [120] defined an atomic C:N range of 3.4–3.8 as being acceptable for radiocarbon dating sheep’s wool, modern camelid fiber samples produced a range of atomic C:N ratios between 3.10 and 3.45 ($n = 85$) [24]. It therefore seems unreasonable to exclude data based on criteria defined for another taxon that produces a distinct type of fiber [127]. For the dataset presented in Fig 2, encompassing 452 analyzed camelid fiber samples from Peru and Chile, a significant number of samples with atomic C:N ratios greater than 4 produced relatively low $\delta^{13}C$ and high $\delta^{15}N$ values. Fourteen samples produced $\delta^{13}C$ values less than $-16 \%$ and $\delta^{15}N$ values greater than $+10 \%$. Of these fourteen, five (36%) had C:N ratios that were greater than 4, while the number of fiber samples in the entire dataset producing C:N ratios greater than 4 was 14 (3% of the total sample). On this basis, we excluded any samples with an atomic C:N ratio over 4 from our analysis.

### Data treatment

When comparisons were made between bone collagen and textile isotopic compositions, the textile $\delta^{13}C$ values were adjusted by $+1.3 \%$ to account for inter-tissue differences in diet-tissue fractionation. The isotopic composition of bone collagen represents the weighted average of foods consumed over a period of several years [128]. While hair grows incrementally and is inert once formed, the nature of textile samples is such that the period of time represented by an isotopic measurement cannot be determined, nor is it certain that a single animal is represented in any particular fiber sample. Therefore, the isotopic compositions of textile samples represent an average dietary intake over an indeterminate amount of time. It is therefore important to generate larger numbers of isotopic measurements of textiles than of bone collagen to adequately capture the variability within a single site or context.

To assess differences in the isotopic compositions between periods or regions, one of the following tests were used: Student’s t-test (normally distributed, equal variances), Welch’s t-test (normally distributed, unequal variances), or Mann Whitney U test (non-normally distributed). Normality was assessed using a Shapiro-Wilk test. Equality of variance was assessed using Levene’s test. The presence of discrete isotopic groups in the textile dataset was assessed using an unweighted pair group method with arithmetic mean cluster analysis with a Euclidean distance function.

The amount of bivariate isotopic variation was estimated using the standard bivariate ellipse in the SIBER package [129]. Ellipse sizes reported in the text are standard ellipse areas corrected for sample size (SEA$_s$). Comparisons between ellipses were performed with 10$^4$ iterative draws (SEA$_d$) with the results being expressed as the percentage of computed ellipses for Group 1 that are larger than the computed ellipses for Group 2; a value of 0.50 indicates the two ellipses are identical in size, while a value of 1 or 0 would indicate that the ellipses for Group 1 are always larger or smaller than those for Group 2.

The cluster analysis was performed using Past 3.20. The SIBER calculations were performed in R 3.0.3; the scripts are included in the supplementary information (S1 File). All other statistical tests were performed using IBM SPSS 23.
Results

Bone collagen

The bone collagen δ\(^{13}\)C and δ\(^{15}\)N values are presented in S1 Table and Fig 3. The camelids from the Late Horizon possessed significantly higher δ\(^{13}\)C values than those dating to the LIP (Welch’s t-test; \(t = -3.46, df = 8.59, p = 0.008\)); the δ\(^{15}\)N values did not differ between the two periods (Welch’s t-test; \(t = -0.46, df = 9.36, p = 0.65\)). There was no overlap between the standard ellipses generated for the camelid bone collagen dating to the LIP and LH (Fig 3). The

Fig 3. Bone collagen δ\(^{13}\)C and δ\(^{15}\)N values for camelids from the Lluta Valley along with the standard bivariate ellipses for the two time periods. Late Intermediate Period samples are indicated by squares and Late Horizon samples are indicated by circles.

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bivariate isotopic variation observed for the LH camelids was much greater than for the LIP camelids (SEA of 10.4 compared to 3.0), with the modeled ellipses of the LH group being larger than the LIP group in 99% of the comparisons.

**Textiles**

The textile carbon and nitrogen isotopic and elemental compositions are presented in S2 Table. There were two distinct groups of textiles, one with lower δ\(^{13}\)C and δ\(^{15}\)N values and one with higher δ\(^{13}\)C and δ\(^{15}\)N values (Fig 4); these groupings were confirmed with a cluster analysis (Fig 5). For the purposes of further analysis, each cluster was considered a distinct data set and they are referred to as Textile Group 1 (δ\(^{13}\)C = −19.77±1.05 ‰, δ\(^{15}\)N = 8.19±2.07 ‰, n = 60) and Textile Group 2 (δ\(^{13}\)C = −14.44±1.55 ‰, δ\(^{15}\)N = +13.97±1.63 ‰, n = 12). Relative to the overall textile sample, the two groups contained similar proportions of samples from the Lluta (45% of Group 1, 44% of overall sample) and Camarones (55% of Group 1, 56% of overall sample) valleys, as well as the LIP (58% of Group 1, 57% of overall sample) and LH (34% of Group 1, 36% of overall sample). Therefore, the presence of these two textile groups could not be explained by a regional or temporal effect.

Within Textile Group 1, samples from the LIP and LH did not differ significantly with respect to their δ\(^{13}\)C (Mann Whitney U test; U = 385.5, p = 0.36) or δ\(^{15}\)N (Student’s t-test; t = 1.70, df = 61, p = 0.09). The textile samples within Group 1 from the Lluta Valley had significantly higher δ\(^{15}\)N values than those from the Camarones Valley (Student’s t-test; t = 3.11, df = 66, p = 0.003), although there were no significant differences in δ\(^{13}\)C between the two valleys (Mann Whitney U test; U = 541, p = 0.86).

After adjusting for differences in fractionation between tissues, Textile Group 1 had similar isotopic compositions to the camelid bone collagen samples from the sites in the Lluta Valley, falling between the LIP and LH bone collagen ellipses (Fig 6). Textile Group 2 possessed markedly higher δ\(^{13}\)C and δ\(^{15}\)N values than either the LIP or LH bone collagen datasets from the Lluta Valley (Fig 6).

Unspun fleece samples had higher δ\(^{13}\)C and δ\(^{15}\)N values (δ\(^{13}\)C = −16.57±4.52 ‰, δ\(^{15}\)N = +9.33±3.70 ‰, n = 15) than spun yarns (δ\(^{13}\)C = −19.19±2.40 ‰, δ\(^{15}\)N = +8.54±2.56 ‰, n = 56). This difference was statistically significant for δ\(^{13}\)C (U = 236, p = 0.01) but not for δ\(^{15}\)N (U = 409, p = 0.88). A higher proportion of the Group 2 textiles consisted of unspun yarns (n = 5 or 50%) relative to Group 1 (n = 10 or 14%).

**Discussion**

**Camelids originating in the highlands**

The bone collagen δ\(^{13}\)C and δ\(^{15}\)N values of the Lluta Valley camelids are consistent with a highland origin. The LIP and LH camelid bone collagen δ\(^{13}\)C and δ\(^{15}\)N values are summarized as standard bivariate ellipses and compared to camelids from other relevant sites where the camelids are known to have been raised in the highlands (Fig 7). Among the three comparative sites, there is a pattern of increasing δ\(^{13}\)C values with increasing latitude, with the lowest values at Chinchawas (~9.5˚S), intermediate values at Tiwanaku (~16.5˚S), and the highest values for sites on the Tulan transect (~23.5˚S). This pattern likely has nothing to do with increasing quantities of C\(_4\) plants in the diet with increasing latitude, but with increasingly high δ\(^{13}\)C values as the puna environment becomes drier moving north to south, transitioning from moist puna to dry puna to salt puna [112, 130]. In light of their δ\(^{15}\)N values, both the LIP and LH camelids from the Lluta Valley sites lived in areas that were more arid than those at either Tiwanaku or Chinchawas. The northern Chilean puna is the most likely origin for these...
Fig 4. Stable carbon and nitrogen isotope compositions of all of the textile samples analyzed.

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Fig 5. Results of the cluster analysis for the textile and human hair samples.

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camelids, but the stark isotopic difference between the LIP and LH camelids from the Lluta Valley sites requires further discussion.

Changes in geographic origins of camelids during the late horizon

The LH camelids from the Lluta Valley can be divided into two groups, one with lower $\delta^{13}C$ and $\delta^{15}N$ values, and one with higher $\delta^{13}C$ and $\delta^{15}N$ values; the latter group is largely responsible for the difference between the two periods (Fig 3). This apparent division among the LH
group may be driven by these camelids originating in two distinct geographic regions, one of which is much drier (for the camelids with the higher $\delta^{13}C$ and $\delta^{15}N$ values) than the other (for the camelids with the lower $\delta^{13}C$ and $\delta^{15}N$ values). Alternatively, camelids may have been drawn from a more diverse range of environments overall during the LH, but because of the small size of our sample, we have simply failed to capture the full range of this variability. Regardless, our data suggest that there was a shift in the range of environments from which camelids were obtained during the LH relative to the LIP.

Fig 7. Interregional comparison of camelid bone collagen isotopic compositions. Standard bivariate ellipses for the camelid bone collagen from the Lluta Valley and various sites where the camelids are believed to have lived in the highlands: Chinchawas [31], Tiwanaku [131], and Tulan (Late Archaic/Early Formative) [132].

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During the LIP, we suggest that the inhabitants of the Lluta Valley acquired their camelid meat from the puna located adjacent to the northern valleys. In the northern valleys, the LIP was a time characterized by regionalization in the wake of the Tiwanaku polity. One crucial point of debate has been whether or not there was physical resettlement of groups from the altiplano into the northern valleys following Tiwanaku’s demise [133, 134]. In a recent synthesis, Muñoz et al. [42] conclude that, although there were Tiwanaku influences during this period, there is no archaeological or bioanthropological evidence to support the presence of Tiwanaku colonies in northernmost Chile. The influence of Tiwanaku is mainly expressed in Cabuza and Tiwanaku pottery types. Cabuza was a locally produced and consumed style that attempted to emulate Tiwanaku forms and decoration. The Tiwanaku style reproduces forms and decorations of the expansive Tiwanaku Phase V, but has strong influences from Moquegua, suggesting its provenience in these valleys in southern Peru, rather than the altiplano [135, 136]. Recently, radiocarbon dating carried out in Cabuza funerary contexts indicates that most of the dates fall within the LIP, suggesting that the Tiwanaku influence may have been associated with people deserting the Titicaca Basin or colonies in Moquegua following Tiwanaku’s demise [137]. Despite the lack of a strong influence of Tiwanaku on the northern Chilean valleys, the isotopic data from the LIP camelids suggests connections with the altiplano. During the LIP, a variety of altiplanic goods (e.g., feathers, copper, obsidian, sulfur, pottery) have been systematically recorded in lowland settlements possibly as a consequence of social interaction networks, which were intensified during this period [41, 138]. Camelids could certainly have been an important part of these interregional networks of interaction and exchange, particularly in light of the fact that the sites analyzed in this study are 40 to 65 km from the contiguous altiplano.

The fact that the LIP and LH camelids from the Lluta Valley were characterized by distinct isotopic compositions suggests either a change in the geographical origin of the camelids or a change in the way in which they were managed. These could be a consequence of the Inca presence in the lowland valleys of northern Chile. Although no investment in state infrastructure is present, significant changes in the ways of life of the local communities, reorganization of the economy and alterations in the political systems have been recorded as result of the Inca control over this area. These changes are expressed in the incorporation of conspicuous Inca prestige goods (e.g., aribilos, khipu, unku, tumi), the concentration of populations in larger villages, alterations of health conditions (intestinal parasites) as a result of overcrowded residences, and the intensification of maize and textile production, which demonstrate clear alterations to the local way of life, although without a visible impact on the architecture [46, 139].

During the LH, rights over resources and lands were claimed as state property by Tawantinsuyu (the Inca Empire) [140]. Camelids were strictly controlled and regulated by the Inca, with three different types of herds: state, church, and community [12]. There were also exclusive regulations for the use of hunting grounds of wild camelids, especially vicuña [141]. Additionally, the Inca state employed redistribution as a socio-political and ideological mechanism to control local populations, although a diverse range of economic structures almost certainly existed within Tawantinsuyu [142]. Among the goods distributed to local communities, wild and domesticated camelids are frequently mentioned in the chronicles [143]. Murra [144] specifies that the camelids redistributed by the state did not come from the community herds, but from the state herds. Chroniclers agree that relatively little camelid meat was consumed during Inca times, except at feasts and ceremonies, although this assertion requires explicit testing with archaeological data [145]. In some Andean regions an increase in the production and/or consumption of camelids during the LH has been identified, typically interpreted
within a framework of access to meat and livestock regulated and centralized by the Inca state, sometimes in the form of state-sponsored feasts [140, 145–150]. Consequently, if the Inca state controlled the flow of camelids or their meat among the conquered provinces through state redistribution networks, then the camelids consumed in the Lluta valley may have had a different geographical origin relative to those of the LIP because they were the result of new animal distribution circuits associated with the redistribution networks controlled by the Inca state. During the Inca occupation of Tiwanaku (Pumapunku complex), a pastoralist area *par excellence*, large quantities of camelids were consumed at state-sponsored feasts. Of the basis of isotopic analyses, most of these camelids had a local origin but some of them originated outside of the *altiplano* in the Titicaca Basin [151], possibly because of the diverse origins of camelids from state herds. Although it cannot be established if the camelid bone samples included in this study were associated with state-sponsored commensal meals, some of them could have arrived in the Lluta Valley via redistributive networks.

**Origins of camelid fiber**

The fact that the isotopic patterns observed for camelid skeletal remains and fiber from textiles are distinct from one another (Fig 6) suggests that animals raised for different purposes (i.e., meat vs. fiber) originated in different geographic areas, consumed different foods, or a combination of these. During the Late Horizon, camelid herds were segregated according to their function: fiber, meat, and cargo [146, 149]. This is consistent with our results, but that fact that there is no difference in the fiber isotopic compositions between the LIP and LH suggests that the Inca did not influence the geographic regions from which fiber was being obtained in the Lluta and Camarones Valleys. Alternatively, there may have been significant changes in the regions of fiber production and the movement of these goods but if these changes occurred within an isotopically homogenous highland environment, it would not be detectable with the methods applied in this study. For example, if fiber production intensified during the Late Horizon (more fiber produced from the same area of land being grazed [152]), possibly driven by the extraction of tribute from some communities and the development of new categories of specialized weavers [11, 44], this scenario may not have left traces in the isotopic compositions of the textiles. On the other hand, if fiber production extensified (more fiber produced from camelids being raised in a larger number of areas), we might expect to see isotopic evidence of localized camelid husbandry, or at least non-altiplanic camelid husbandry, exclusively in the Late Horizon. Some chronicles indicate that while for local textile needs fiber from the community was used, for the *mit’a* obligations, in contrast, the Inca state provided the fiber, which came from state deposits [143, 144], likely located in the highlands. The presence of weaving tools in households in the valleys of northern Chile suggest that textiles were being manufactured locally even if the fiber was being imported from the highlands.

Considering the separation of herds for fiber and herds for meat as well as the diverse fiber used for local needs versus for *mit’a*, the scenario outlined in the preceding paragraph could suggest different circuits of distribution for meat and fiber during the Late Horizon. Textile production for local consumption, which constitutes the majority of textile samples recovered from these archaeological sites, continued to be dependent on the highlands for fiber, as was during case during the LIP. On the contrary, for the textiles manufactured through *mit’a* labor, we expect that the raw material would have originated in state fiber deposits. Moreover, if the *mit’a* used either state or community fiber, it would likely not be possible to recognize this distinction in the archaeological record because these textiles should have been redirected from local households for state purposes and would not have remained in the area where the fiber was produced [11]. Therefore, *mit’a* textiles should have low archaeological visibility in
domestic contexts such as those sampled in this study. In some domestic contexts of the Lluta Valley where important transformations of the Inca state have been verified, including the relocation of populations and the presence of several khipu, a remarkable increase in spinning and weaving tools has been identified, which is interpreted as a possible result of textile mit’a obligations [44]. Isotopic analyses from contexts such as this may shed light on any changes in fiber production during the Late Horizon.

**Fiber originating outside of the highlands**

A subset of the textile samples from both the LIP and LH have isotopic compositions that are inconsistent with camelids that lived in the highlands (Figs 4 and 5). Given the greater importance of llamas for meat and their adaptability to a wider range of environments than alpacas [153], which were primarily fiber producers [20], it is surprising that the textiles, rather than camelid bone samples, appear to have non-highland origins. The issue of raising camelids in the lowlands has not been studied systematically in northern Chile, either through the application of isotopic analysis or traditional archaeological methodologies. Archaeological evidence for the maintenance of camelid herds in the lowlands (although not their permanent presence) includes corral-type structures found in villages [45, 52, 154–156] and concentrations of camelid dung [45, 52, 157–160]. For northern Chile, sixteenth century ethnohistorical accounts describe the maintenance of camelid herds in the lowlands and the tribute of livestock and manufactured textiles to the Spanish Crown by local indigenous groups from Ilo, Tacna, Arica, and Tarapacá [143, 161, 162]. If there were local herds oriented towards fiber production, we would expect to see a significant quantity of unspun fleece with local isotopic signatures. Consistent with this expectations, only 14% of the camelid fibers analyzed had isotopic compositions consistent with a local origin but a disproportionately high number of these (50%) were unspun fleece rather than spun yarns.

In addition to the textiles manufactured from camelid fiber, three textile fragments from Huancarane were made of human hair. These three samples possess $\delta^{13}C$ and $\delta^{15}N$ values that are very similar to the group identified as non-highland camelids (Fig 4). These human hair isotopic compositions are comparable to other LIP and LH data from the region, although humans from northern Chile possess highly variable tissue isotopic compositions [163–167]. The human $\delta^{13}C$ and $\delta^{15}N$ values are consistent with a substantial amount of maize in the diet rather than marine foods as marine organisms from northern Chile possess extremely high $\delta^{15}N$ values due to strong upwelling and denitrification in this region [168, 169]. Human populations in this region that relied on marine foods to a significant degree tend to the highest tissue $\delta^{15}N$ values among any human group, frequently in excess of +20 ‰ or even +25 ‰ [164, 170], substantially higher than those observed in this study: $\delta^{15}N = +13.9$ ‰, +15.0 ‰, and +15.4 ‰.

The humans from which the hair was obtained were almost certainly locals and the fact that the non-highland textile groups possesses very similar isotopic compositions suggests that these animals may have consumed a similar range of agricultural plants to the humans living in the Camarones Valley. If camelids were kept in these valleys, they would have needed to consume significant quantities of agricultural plants because there is scarce wild vegetation on which they could feed, although there may have been some fields composed of halophytic grasses (Distichlis spicata) growing close to the coast at the river mouth based on the presence of this plant today [171]. Distichlis spicata is a $C_4$ plant and given its association with salty environments, it might be expected to possess relatively high $\delta^{15}N$ values [172] but this has not been observed for northern Chile ($\delta^{15}N = +4.6\pm3.1$ ‰) [173] or northern Peru (−3.2 ‰) [111]. The similarity in both $\delta^{13}C$ and $\delta^{15}N$ values between the camelid fibers and the human
hairs are consistent with both humans and camelids consuming a similar range of agricultural plants, suggesting that some animals were kept locally. An alternative possibility is that the non-highland camelid hair was derived from wild guanacos living at these lower altitudes. If, however, guanacos could consume a sufficient quantity of local plants, it begs the question as to why this would not have been equally plausible for llamas.

The absence of any non-highland isotopic compositions in the camelid bone collagen similar to that observed in the textiles may simply be a product of sample size, or it may imply that the primary motivation for keeping these animals locally was for fiber production rather than for meat or transport, underscoring the quintessential importance of textiles and camelid fiber in the Andean region [19, 174–176]. Niemeyer and Schiappacasse [52] estimated that given the low number of juvenile camelids identified in faunal assemblages, animal husbandry was oriented towards fiber production and/or transport, rather than for meat. However, they believed that the fiber was obtained from the adjacent altiplano because the environment near Huancarane would not be suitable for pastoral activities. They envisioned two strategies being employed by the local people: (1) possession of pastoral lands and herds in the highlands, and (2) the acquisition of livestock through exchange with llamas caravanners. These actions were also observed during the 1970s by these authors in this sector of the Camarones Valley. Our data suggest that by at least the LIP, groups living in the lower Camarones and Lluta Valleys kept small numbers of animals locally, but acquired the majority of their fiber through exchange with groups in the highlands. The reliance on imported fiber may have been driven by the limitations of the environment for camelid husbandry, necessitating an external supply.

**Conclusion**

Our data suggest that the northern Chilean valleys were not able to support the same level of camelid husbandry as the northern valleys of Peru, but people were still attempting to raise small numbers of animals to produce fiber for textiles since at least the Late Intermediate Period. There was a significant shift in the isotopic compositions of camelid bone collagen between the LIP and the LH in the Lluta Valley, possibly because of alterations made to the distribution networks for camelids instituted by the Inca. These changes were not, however, visible in the textiles, which had comparable isotopic compositions between the LIP and LH.

**Supporting information**

S1 Table. Isotopic and elemental compositions for the bone collagen samples analyzed with contextual information.
(XLSX)

S2 Table. Isotopic and elemental compositions for the textile samples analyzed with contextual information.
(XLSX)

S1 Appendix. Supplementary methods. Relevant details on analytical uncertainty, quality assurance, and quality control.
(DOCX)

S1 File. R scripts used in the analysis.
(R)
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References

1. Lau GF. Animal resources and Recuay cultural transformations at Chinchawas (Ancash, Peru). And Past. 2007; 8:449–76.
2. Pozorski SG. Subsistence systems in the Chimú State. In: Moseley ME, Day KC, editors. Chan Chan: Andean Desert City. Albuquerque: University of New Mexico Press; 1982. p. 177–96.
3. Hesse B. Archaeological Evidence for Camelid Exploitation in the Chilean Andes. Saugetierkundliche Mitteilungen. 1982; 30:201–11.
4. Valenzuela D, Santoro CM, Capriles JM, Quinteros MJ, Peredo R, Gayo EM, et al. Consumption of animals beyond diet in the Atacama Desert, northern Chile (13,000–410BP): Comparing rock art motifs and archaeofaunal records. J Anthropol Archaeol. 2015; 40:250–65. https://doi.org/10.1016/j.jaa.2015.09.004
5. Dransart PZ. Earth, Water, Fleece, and Fabric: An Ethnography and Archaeology of Andean Camelid Herding. London: Routledge; 2002.
6. Tripcevich N. The Ethnoarchaeology of a Cotahuasi Salt Caravan. In: Capriles JM, Tripcevich N, editors. The Archaeology of Andean Pastoralism. Albuquerque: University of New Mexico Press; 2016. p. 211–29.
7. Nielsen AM. Ethnoarchaeological Perspectives on Caravan Trade in the South-Central Andes. In: Kuznar LA, editor. Ethnoarchaeology of Andean South America: Contributions to Archaeological Method and Theory. Ann Arbor: International Monographs in Prehistory. Ethnoarchaeological Series 4; 2001. p. 163–201.
8. Chepstow-Lusty AJ. Agro-pastoral and social change in the Cuzco heartland of Peru: a brief history using environmental proxies. Antiquity. 2011; 85:570–82. https://doi.org/10.1017/S0003598X0006796X
9. Szpak P, Chiou KL. A comparison of nitrogen isotope compositions of charred and desiccated botanical remains from northern Peru. Vegetation History and Archaeobotany. 2019. https://doi.org/10.1007/s00334-019-00761-2
10. Dransart P. Llamas, herders and the exploitation of raw materials in the Atacama desert. World Archaeol. 1991; 22(3):304–19. https://doi.org/10.1080/00438243.1991.9980148
11. Costin CL. Housewives, Chosen Women, Skilled Men: Cloth Production and Social Identity in the Late Prehispanic Andes. Archeological Papers of the American Anthropological Association. 1998; 8 (1):123–41.
12. Murra JV. Herds and herders in the Inca state. In: Leeds A, Vayda AP, editors. Man, Culture, and Animals: The Role of Animals in Human Ecological Adjustments. Washington, D.C.: American Association for the Advancement of Science; 1965. p. 185–215.

13. Murra JV. The Economic Organization of the Inka State. Greenwich: JAI Press; 1980. 208 p.

14. Costin CL. Textiles, women, and political economy in late Prehispanic Peru. In: Isaac BL, editor. Research in Economic Anthropology, Volume 14. 14. Greenwich: JAI Press; 1993. p. 3–28.

15. Murra JV. La mit’a al Tawantinsuyu: prestaciones de los grupos étnicos. Chungara. 1980; 10:77–94.

16. Costin CL. Cloth production and gender relations in the Inka Empire. In: Peregrine P, Ember C, Ember M, editors. Archaeology Original Readings in Methods and Practice. London: Prentice Hall; 2002. p. 261–9.

17. Costin CL. Textiles and Chimú identity under Inka Hegemony on the North Coast of Peru. In: Little WE, McAnany PA, editors. Textile Economies: Power and Value from the Local to the Transnational. Lanham, MD: AltaMira Press; 2011. p. 101–24.

18. Oakland Rodman A. Textiles and Ethnicity: Tiwanaku in San Pedro de Atacama, North Chile. Lat Am Antiq. 1992; 3(4):316–40. https://doi.org/10.2307/971952

19. Boytner R. Clothing the social world. In: Silverman H, editor. Andean Archaeology. Malden, MA: Blackwell; 2004. p. 130–45.

20. Bonavia D. The South American Camelids. Los Angeles: Cotsen Institute of Archaeology, University of California; 2008. 628 p.

21. Troll C. Las Culturas Superiores Andinas y el medio geográfico. Lima, Peru: Publicaciones del Instituto de Geografía, Facultad de Letras, Universidad Nacional Mayor de San Marcos; 1958.

22. Rostworowski M. Recursos Naturales Renovables y Pesca, siglos XVI y XVII. Lima, Peru: Instituto de Estudios Peruanos; 1981.

23. Szpak P, Millaire J-F, White CD, Bourget S, Longstaffe FJ. Life Histories of Sacrificed Camelids from Huancaico (Virú Valley). In: Klaus HD, Toyne JM, editors. Reconstructing Sacrifice on the North Coast of Peru: Archaeological Studies of Ritual Violence in the Ancient Andes. Austin: University of Texas Press; 2016. p. 319–41.

24. Szpak P, Millaire J-F, White CD, Longstaffe FJ. Small scale camelid husbandry on the north coast of Peru (Virú Valley): Insight from stable isotope analysis. J Anthropol Archaeol. 2014; 36:110–29. https://doi.org/10.1016/j.jaa.2013.09.008

25. Tomczyk W, Giersz M, Soltysiak A, Kamenov G, Krigbaum J. Patterns of camelid management in Wari Empire reconstructed using multiple stable isotope analysis: evidence from Castillo de Huarmey, northern coast of Peru. Archaeol Anthropol Sci. 2018. https://doi.org/10.1002/1613.12052

26. Szpak P, Millaire J-F, Chapdelaine C, White CD, Longstaffe FJ. An Integrated isotopic study of Early Intermediate Period camelid husbandry in the Santa Valley, Peru. Environ Archaeol. 2019:1–17. https://doi.org/10.1080/14614103.2019.1583302

27. Santana-Sagredo F, Dufour E, Goepfert N, Zazzo A, Franco Jordán R, Vásquez Sánchez S. New Bioarchaeological Evidence and Radiocarbon Dates from the Lambayeque/Sicán Culture Camelids from the El Brujo Complex (Northern Coast of Peru): Implications for Funerary and Herd Management Practices. Environ Archaeol. 2018:1–20. https://doi.org/10.1080/14614103.2018.1556960

28. Dufour E, Goepfert N, Le Neün M, Prieto G, Verano JW. Life History and Origin of the Camelids Provisoning a Mass Killing Sacrifice During the Chimú Period: Insight from Stable Isotopes. Environ Archaeol. 2018:1–14. https://doi.org/10.1080/14614103.2018.1498165

29. Finucane B, Agurto PM, Isbell WH. Human and animal diet at Conchopata, Peru: stable isotope evidence for maize agriculture and animal management practices during the Middle Horizon. J Archaeol Sci. 2006; 33(12):1766–76. https://doi.org/10.1016/j.jas.2006.03.012

30. Shimada M, Shimada I. Prehistoric llama breeding and herding on the north coast of Peru. Amer Antiq. 1985; 50(1):3–28. https://doi.org/10.2307/280631

31. Szpak P, Millaire J-F, White CD, Lau GF, Surette F, Longstaffe FJ. Origins of Prehispanic Camelid Wool Textiles from the North and Central Coasts of Peru traced by Carbon and Nitrogen Isotopic Analyses. Curr Anthropol. 2015; 56(3):449–59. https://doi.org/10.1086/680873

32. Szpak P, Millaire JF, White CD, Donnan CB, Longstaffe FJ. Stable Isotope Sourcing of Wool from Textiles at Pacatnamú. Archaeometry. 2018; 60(3):612–27. https://doi.org/10.1111/arcm.12342

33. Rowe AP. Textiles from the burial platform of Las Avispas at Chan Chan. Nawpa Pacha. 1980; 18:81–164. https://doi.org/10.1179/naw.1980.18.1.006

34. Pinto R, Barria I, Marquet PA. Geographical distribution of Tillandsia lomas in the Atacama Desert, northern Chile. J Arid Environ. 2006; 65(4):543–52. https://doi.org/10.1016/j.jaridenv.2005.08.015
35. Grosjean M, Santoro CM, Thompson LG, Núñez L, Standen VG. Mid-Holocene climate and culture change in the South Central Andes. In: Anderson DG, Maasch KA, Sandweiss DH, editors. Climate Change and Cultural Dynamics: A Global Perspective on Mid-Holocene Transitions. San Diego: Academic Press; 2007. p. 51–115.

36. Niemeyer H. Hoya hidrográficas de Chile. Primera Región. Santiago, Chile: Ministerio de Obras Públicas, Dirección General de Aguas; 1980.

37. Schull WJ, Razmilic B, Figueroa L, Gonzalez M. Trace metals. In: Schull WJ, Rothhammer F, editors. The Aymara: Strategies of Human Adaptation to a Rigorous Environment. Dordrecht: Kluwer Academic; 1990. p. 33–44.

38. Gayo EM, Latorre C, Jordan TE, Nester PL, Estay SA, Ojeda KF, et al. Late Quaternary hydrological and ecological changes in the hyperarid core of the northern Atacama Desert (~21˚S). Earth-Sci Rev. 2012; 113(3):120–40. https://doi.org/10.1016/j.earscirev.2012.04.003

39. Gayo EM, Latorre C, Santoro CM, Maldonado A, De Pol-Holz R. Hydroclimate variability in the low-elevation Atacama Desert over the last 2500 years. Climate of the Past. 2012; 8:287–306. https://doi.org/10.5194/cp-8-287-2012

40. Latorre C, González FJ, Houston J, Rojas M, Mujica MI. Reliable mean annual rainfall estimates using chinchilla rat (Abrocoma) middens from the Atacama Desert during the late Quaternary. EOS Trans Am Geophys Union. 2010; 91(26):PP 23B–05.

41. Santoro CM, Dillehay TD, Hidalgo J, Valenzuela D, Romero AL, Rothhammer F, et al. The third case of John Murra’s verticality revisited on the coasts of the central and south-central Andes. Chungara Revista de Antropología Chilena. 2010; 42(1):325–40. ISI:000278566300038.

42. Muñoz I, Aguero C, Valenzuela D. Poblaciones prehispánicas de los Valles Occidentales del norte de Chile: desde el Período Formativo al Intermedio Tardío (ca. 1.000 años a.C. a 1.400 años d.C.). In: Falabella F, Uribe M, Sanhueza C, Alconini S, Hidalgo J, editors. Prehistoria en Chile Desde sus primeros habitantes hasta los Incas. Santiago: Editorial Universitaria & Sociedad Chilena de Arqueología; 2016. p. 181–237.

43. Romero A, Santoro CM, Santos M. Asentamientos y organización sociopolítica en los tramos bajo y medio del Valle de Lluta. Actas del 3er Congreso Chileno de Antropología, vol II. Santiago, Chile: Colegio de Antropólogos de Chile; 2000. p. 696–706.

44. Santoro CM. Late Prehistoric Regional Interaction and Social Change in a Coastal Valley of Northern Chile. Oxford: BAR International Series 2823; 2016.

45. Santoro CM, Muñoz I. Poblaciones prehispánicas de los Valles Occidentales del norte de Chile: desde el Período Formativo al Intermedio Tardío (ca. 1.000 años a.C. a 1.400 años d.C.). In: Falabella F, Uribe M, Sanhueza C, Alconini S, Hidalgo J, editors. Prehistoria en Chile Desde sus primeros habitantes hasta los Incas. Santiago: Editorial Universitaria & Sociedad Chilena de Arqueología; 2016. p. 181–237.

46. Niemeyer H, Schiappacesse V. Aportes al conocimiento del Período Tardío del extremo norte de Chile: Analisis del sector de Huanacarane del valle de Camarones. Chungara. 1981; 7:144–71.

47. Uribe M. Cerámica arqueológica de la quebrada de Camarones: Sector Huancarane. Unpublished report. FONDECYT 1151046. 2016.

48. Hobson KA. Tracing origins and migration of wildlife using stable isotopes: a review. Oecologia. 1999; 120(3):314–26. https://doi.org/10.1007/s004420050865 PMID: 28308009

49. Frei KM, Bjerrengaard L. Provenance investigations of raw materials in pre- Columbian textiles from Pachacamac: strontium isotope analyses. In: Bjerrengaard L, Peters A, editors. PreColumbian Textile Conference VII. Lincoln, Nebraska: Zea Books; 2017. p. 387–97.
60. Murphy BP, Bowman DMJS. Kangaroo metabolism does not cause the relationship between bone collagen δ13C and δ15N values in herbivores in hot and arid environments caused by diet or animal physiology? Funct Ecol. 2006; 20(6):1062–9. https://doi.org/10.1111/j.1365-2435.2006.01186.x

61. DeNiro MJ, Epstein S. Influence of diet on the distribution of carbon isotopes in animals. Geochim Cosmochim Acta. 1978; 42(5):495–506. https://doi.org/10.1016/0016-7037(78)90199-0

62. DeNiro MJ, Epstein S. Influence of diet on the distribution of nitrogen isotopes in animals. Geochim Cosmochim Acta. 1981; 45(3):341–51. https://doi.org/10.1016/0016-7037(81)90244-1

63. Ambrose SH, Norr L. Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: Lambert JB, Grupe G, editors. Prehistoric Human Bone: Archaeology at the Molecular Level. New York: Springer-Verlag; 1993. p. 1–37.

64. Jim S, Jones V, Ambrose SH, Evershed RP. Quantifying dietary macronutrient sources of carbon for bone collagen biosynthesis using natural abundance stable carbon isotope analysis. Br J Nutr. 2006; 95(6):1055–62. https://doi.org/10.1079/bjn20051685 ISI:000238200700005 PMID: 16768826

65. Murphy BP, Bowman DMJS. Kangaroo metabolism does not cause the relationship between bone collagen δ13C and δ15N and water availability. Funct Ecol. 2006; 20(6):1062–9. https://doi.org/10.1111/j.1365-2435.2006.01186.x

66. Hartman G. Are elevated δ15N values in herbivores in hot and arid environments caused by diet or animal physiology? Funct Ecol. 2011; 25(1):122–31. https://doi.org/10.1111/j.1365-2435.2010.01782.x

67. Farquhar GD, Ehleringer JR, Hubick KT. Carbon Isotope Discrimination and Photosynthesis. Annu Rev Plant Physiol Plant Mol Biol. 1989; 40(1):503–37. https://doi.org/10.1146/annurev.pp.40.060189.002443

68. Högberg P. Tansley Review No. 95. 15N natural abundance in soil-plant systems. New Phytol. 1997; 137(2):179–203. https://doi.org/10.1046/j.1469-8137.1997.00808.x

69. Ehleringer JR. Carbon Isotope Ratios and Physiological Processes in Aridland Plants. In: Rundel PW, Ehleringer JR, Nagy KA, editors. Stable Isotopes in Ecological Research. New York: Springer-Verlag; 1989. p. 41–54.

70. Kohn MJ. Carbon isotope compositions of terrestrial C3 plants as indicators of (paleo)ecology and (paleo)climate. Proc Natl Acad Sci U S A. 2010; 107(46):19691–5. https://doi.org/10.1073/pnas.1004933107 PMID: 21041671

71. O'Leary MH. Carbon Isotopes in Photosynthesis. Bioscience. 1988; 38(5):328–36. https://doi.org/10.1073/pnas.1004933107 PMID: 21041671

72. Cernusak LA, Ubierna N, Winter K, Holtum JAM, Marshall JD, Farquhar GD. Environmental and physiological determinants of carbon isotope discrimination in terrestrial plants. New Phytol. 2013; 200(4):950–65. https://doi.org/10.1111/nph.12423 PMID: 23902460

73. Stewart GR, Turnbull MH, Schmidt S, Erskine PD. 13C natural abundance in plant communities along a rainfall gradient: a biological integrator of water availability. Aust J Plant Physiol. 1995; 22(1):51–5. https://doi.org/10.1071/PP9950051

74. Austin AT, Vitousek PM. Nutrient dynamics on a precipitation gradient in Hawai‘i. Oecologia. 1998; 113(4):519–29. https://doi.org/10.1007/s004420050405 PMID: 28308032

75. Swap RJ, Aranibar JN, Dowty PR, Gilhooly WP III, Macko SA. Natural abundance of 13C and 15N in C3 and C4 vegetation of southern Africa: patterns and implications. Glob Change Biol. 2004; 10(3):350–8. https://doi.org/10.1111/j.1365-2486.2003.00702.x

76. Sarris D, Siegwolf R, Körner C. Inter- and intra-annual stable carbon and oxygen isotope signals in response to drought in Mediterranean pines. Agricultural and Forest Meteorology. 2013; 168:59–68. https://doi.org/10.1016/j.agrformet.2012.08.007
77. Schulze ED, Ellis R, Schulze W, Trimborn P, Ziegler H. Diversity, metabolic types and $\delta^{13}$C carbon isotope ratios in the grass flora of Namibia in relation to growth form, precipitation and habitat conditions. Oecologia. 1996; 106(3):352–69. https://doi.org/10.1007/BF00334563 PMID: 28307323

78. Quade J, Rech JA, Latorre C, Betancourt JL, Gleason E, Kalin MTK. Soils at the hyperarid margin: The isotopic composition of soil carbonate from the Atacama Desert, Northern Chile. Geochim Cosmochim Acta. 2007; 71(15):3772–95. https://doi.org/10.1016/j.gca.2007.02.016

79. Rundel PW, Gibson AC, Midgley GS, Wand SJ, Palma B, Kleier C, et al. Ecological and ecophysiological patterns in a pre-altiplano shrubland of the Andean Cordillera in northern Chile. Plant Ecol. 2002; 169(2):179. https://doi.org/10.1023/a:102607571045

80. Long SP. Environmental Responses. In: Sage RF, Monson RK, editors. C4 Plant Biology. San Diego: Academic Press; 1999. p. 215–49.

81. Sage RF, Wedin DA, Li M. The Biogeography of C4 Photosynthesis: Patterns and Controlling Factors. In: Sage RF, Monson RK, editors. C4 Plant Biology. San Diego: Academic Press; 1999. p. 313–74.

82. Jim S, Ambrose SH, Evershed RP. Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen and apatite: implications for their use in palaeodietary reconstruction. Geochim Cosmochim Acta. 2004; 68(1):61–72. https://doi.org/10.1016/S0016-7037(03)00216-3

83. Guy RD, Reid DM, Krouse HR. Shifts in carbon isotope ratios of two C3 halophytes under natural and artificial conditions. Oecologia. 1980; 44(2):241–7. https://doi.org/10.1007/BF00572686 PMID: 28310563

84. Farquhar GD, Ball MC, Caemmerer S, Roksandic Z. Effect of salinity and humidity on $\delta^{13}$C value of halophytes—Evidence for diffusional isotope fractionation determined by the ratio of intercellular/ atmospheric partial pressure of CO$_2$ under different environmental conditions. Oecologia. 1982; 52 (1):121–4. https://doi.org/10.1007/BF00349020 PMID: 28310117

85. Brugnoli E, Lauteri M. Effects of Salinity on Stomatal Conductance, Photosynthetic Capacity, and Carbon Isotope Discrimination of Salt-Tolerant (Gossypium hirsutum L.) and Salt-Sensitive (Phaseolus vulgaris L.) C3 Non-Halophytes. Plant Physiol. 1991; 95(2):628–35. https://doi.org/10.1104/pp.95.2.628 PMID: 16688029

86. van der Merwe NJ, Medina E. Photosynthesis and $^{13}$C/$^{12}$C ratios in Amazonian rain forests. Geochim Cosmochim Acta. 1989; 53(5):1091–4. https://doi.org/10.1016/0016-7037(89)90213-5

87. Bonafini M, Pellegrini M, Ditchfield P, Pollard AM. Investigation of the ‘canopy effect’ in the isotope ecology of temperate woodlands. J Archaeol Sci. 2013; 40(11):3926–35. https://doi.org/10.1016/j.jas.2013.03.028

88. Graham HV, Patzkowsky ME, Wing SL, Parker GG, Fogel ML, Freeman KH. Isotopic characteristics of canopies in simulated leaf assemblages. Geochim Cosmochim Acta. 2014; 144:82–95. https://doi.org/10.1016/j.gca.2014.08.032

89. Touilaine B. Nitrate uptake by roots—transporters and root development. In: De Kok LJ, Stulen I, editors. Nitrogen Acquisition and Assimilation in Higher Plants. Dordrecht: Kluwer Academic; 2004. p. 1–34.

90. Ramos J, Bisseling T. Symbiotic nitrogen fixation. In: De Kok LJ, Stulen I, editors. Nitrogen Acquisition and Assimilation in Higher Plants. Dordrecht: Kluwer Academic; 2004. p. 99–131.

91. Näsholm T, Kielland K, Ganeter U. Uptake of organic nitrogen by plants. New Phytol. 2009; 183(4):980–92. https://doi.org/10.1111/j.1469-8137.2009.02917.x PMID: 19563444

92. Delwiche CC, Zinke PJ, Johnson CM, Virginia RA. Nitrogen isotope distribution as a presumptive indicator of nitrogen fixation. Botanical Gazette. 1979; 140:S65–S9. https://doi.org/10.1086/337037

93. Yoneyama T, Muraoka T, Murakami T, Boonkerd N. Natural abundance of $^{15}$N in tropical plants with emphasis on tree legumes. Plant Soil. 1993; 153(2):295–304. https://doi.org/10.1007/bf00130303

94. Mariotti A. Atmospheric nitrogen is a reliable standard for natural $^{15}$N abundance measurements. Nature. 1983; 303(5919):685–7. https://doi.org/10.1038/303685a0

95. Delwiche CC, Zinke PJ, Johnson CM, Virginia RA. Nitrogen isotope distribution as a presumptive indicator of nitrogen fixation. Botanical Gazette. 1979; 140:S65–S9. https://doi.org/10.1086/337037

96. Yoneyama T, Muraoka T, Murakami T, Boonkerd N. Natural abundance of $^{15}$N in tropical plants with emphasis on tree legumes. Plant Soil. 1993; 153(2):295–304. https://doi.org/10.1007/bf00130303

97. Mariotti A. Atmospheric nitrogen is a reliable standard for natural $^{15}$N abundance measurements. Nature. 1983; 303(5919):685–7. https://doi.org/10.1038/303685a0

98. Craine JM, Elmore AJ, Aidar MPM, Bustamante M, Dawson TE, Hobbie EA, et al. Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. New Phytol. 2009; 183(4):980–92. https://doi.org/10.1111/j.1469-8137.2009.02917.x PMID: 19563444
99. Hobbie EA, Högberg P. Nitrogen isotopes link mycorrhizal fungi and plants to nitrogen dynamics. New Phytol. 2012; 196(2):367–82. https://doi.org/10.1111/j.1469-8137.2012.03400.x PMID: 22963677

100. Read DJ. Mycorrhizas in ecosystems. Experientia. 1991; 47(4):376–91. https://doi.org/10.1007/BF01972080

101. Soudzilovskaia NA, Vaessen S, van’t Zelfde M, Raes N. Global Patterns of Mycorrhizal Distribution and Their Environmental Drivers. In: Tedersoo L, editor. Biogeography of Mycorrhizal Symbiosis. Cham, Switzerland: Springer; 2017. p. 223–35.

102. Geml J. Altitudinal Gradients in Mycorrhizal Symbioses: The Current State of Knowledge on How Richness and Community Structure Change with Elevation. In: Tedersoo L, editor. Biogeography of Mycorrhizal Symbioses. Cham, Switzerland: Springer; 2017. p. 107–23.

103. Bogaard A, Heaton THE, Poulton P, Merbach I. The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. J Archaeol Sci. 2007; 34(3):335–43. https://doi.org/10.1016/j.jas.2006.04.009

104. Fraser RA, Bogaard A, Heaton T, Charles M, Jones G, Christensen BT, et al. Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeobotanical approach to the inference of land use and dietary practices. J Archaeol Sci. 2011; 38(10):2790–804. https://doi.org/10.1016/j.jas.2011.06.024

105. Szpak P, Millaire J-F, White CD, Longstaffe FJ. Influence of seabird guano and camelid dung fertilization on the nitrogen isotopic composition of field-grown maize (Zea mays). J Archaeol Sci. 2012; 39(12):3721–40. https://doi.org/10.1016/j.jas.2012.06.035

106. Szpak P, Longstaffe FJ, Millaire J-F, White CD. Stable Isotope Biogeochemistry of Seabird Guano Fertilization: Results from Growth Chamber Studies with Maize (Zea mays). PLoS ONE. 2012; 7(3):e33741. Epub 2012/04/06. https://doi.org/10.1371/journal.pone.0033741 PMID: 22479435; PubMed Central PMCID: PMC3316503.

107. Santana-Sagredo F, Schulting R, Lee-Thorp J, Agüero C, Uribe M, Lemp C. Nitrogen isotopic composition of soil and plant nitrogen. Global Biogeochem Cycles. 2003; 17(3):1031. https://doi.org/10.1029/2002gb001903

108. Martinelli LA, Piccolo MC, Townsend AR, Vitousek PM, Cuevas E, McDowell W, et al. Nitrogen stable isotope composition of leaves and soil: Tropical versus temperate forests. Biogeochemistry. 1999; 46(1):45–65. https://doi.org/10.1023/a:1006100128782

109. Handley LL, Austin AT, Stewart GR, Robinson D, Scrimgeour CM, Raven JA, et al. The 15N natural abundance (δ15N) of ecosystem samples reflects measures of water availability. Aust J Plant Physiol. 1999; 26(2):185–99. https://doi.org/10.1071/PP98146

110. Szpak P, White CD, Longstaffe FJ, Millaire J-F, Vásquez Sánchez VF. Carbon and Nitrogen Isotopic Survey of Northern Peruvian Plants: Baselines for Paleoecological and Paleoclimatological Studies. PLoS ONE. 2013; 8(1):e53763. https://doi.org/10.1371/journal.pone.0053763 PMID: 23341996

111. Santoro C, Nuñez L. Hunters of the dry puna and the salt puna in northern Chile. And Past. 1987; 1:57–109.

112. Díaz FP, Frugone M, Gutiérrez RA, Latorre C. Nitrogen cycling in an extreme hyperarid environment inferred from δ15N analyses of plants, soils and herbivore diet. Sci Rep. 2016; 6:22226. https://doi.org/10.1038/srep22226 PMID: 26956399

113. Samec CT, Yacobaccio HD, Panarello HO. Carbon and nitrogen isotope composition of natural pastures in the dry Puna of Argentina: a baseline for the study of prehistoric herd management strategies. Archaeol Anthropol Sci. 2017; 9(2):153–63. https://doi.org/10.1007/s12520-015-0263-2

114. Minagawa M, Wada E. Stepwise enrichment of δ15N along food chains: Further evidence and the relation between δ15N and animal age. Geochim Cosmochim Acta. 1984; 48(5):1135–40. https://doi.org/10.1016/0016-7037(84)90204-7

115. Qi H, Coplen TB, Geilmann H, Brand WA, Böhike JK. Two new organic reference materials for δ13C and δ15N measurements and a new value for the δ13C of NBS 22 oil. Rapid Commun Mass Spectrom. 2003; 17(22):2483–7. https://doi.org/10.1002/rcm.1219 PMID: 14608617

116. Qi H, Coplen TB, Mroczkowski SJ, Brand WA, Brandes L, Geilmann H, et al. A new organic reference material, L-glutamic acid, USGS41a, for δ13C and δ15N measurements – a replacement for USGS41. Rapid Commun Mass Spectrom. 2016; 30(7):859–66. https://doi.org/10.1002/rcm.7510 PMID: 26966997

117. Schimmelmann A, Qi H, Coplen TB, Brand WA, Fong J, Meier-Augenstein W, et al. Organic Reference Materials for Hydrogen, and Nitrogen Stable Isotope-Ratio Measurements: Caffeines, n-
Camelid husbandry in the Atacama Desert? An isotopic study from northern Chile

Akanes, Fatty Acid Methyl Esters, Glycines, I-Valines, Polyethylene, and Oils. Anal Chem. 2016; 88 (8):4294–302. https://doi.org/10.1021/acs.analchem.5b04392 PMID: 26974360

Szpak P, Metcalfe JZ, Macdonald RA. Best Practices for Calibrating and Reporting Stable Isotope Measurements in Archaeology. J Archaeol Sci Rep. 2017; 13:609–16. https://doi.org/10.1016/j.jasrep.2017.05.007

Boudin M, Bonafini M, Berghé IV, Maquoi M-C. Naturally Dyed Wool and Silk and Their Atomic C:N Ratio for Quality Control of 14C Sample Treatment. Radiocarbon. 2016; 58(1):55–68. Epub 01/12. https://doi.org/10.1017/RDC.2015.5

don Holstein ICC, Penkman KEH, Peacock EE, Collins MJ. Wet degradation of keratin proteins: linking amino acid, elemental and isotopic composition. Rapid Commun Mass Spectrom. 2014; 28(19):2121–33. https://doi.org/10.1002/rcm.6999 PMID: 25156602

Ambrose SH. Preparation and characterization of bone and tooth collagen for isotopic analysis. J Archaeol Sci. 1990; 17(4):431–51. https://doi.org/10.1016/0305-4403(90)90007-R

DeNiro MJ. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeoecological reconstruction. Nature. 1985; 317(6040):806–9. https://doi.org/10.1038/317806a0

van Klinken GJ. Bone Collagen Quality Indicators for Palaeoecological and Radiocarbon Measurements. J Archaeol Sci. 1999; 26(6):687–95. https://doi.org/10.1006/jas.1998.0385

DeNiro MJ, Weiner S. Chemical, enzymatic and spectroscopic characterization of "collagen" and other organic fractions from prehistoric bones. Geochim Cosmochim Acta. 1988; 52(9):2197–206.

Schoeninger MJ, Moore KM, Murray ML, Kingston JD. Detection of bone preservation in archaeologically and fossil samples. Appl Geochem. 1989; 4(3):281–92. https://doi.org/10.1016/0883-2927(89)90030-9

Thomas A, Harland DP, Clerens S, Deb-Choudhury S, Vernon JA, Krsinic GL, et al. Interspecies Comparisons in the Aging of Elephant and African Wild Dog Bone. Biol Lett. 2005; 1(4):580–2. https://doi.org/10.1098/rsbl.2005.0526

Hedges REM, Clement JG, Thomas DL, O'Connell TC. Collagen turnover in the adult femoral mid-shaft: Modeled from anthropogenic radiocarbon tracer measurements. Am J Phys Anthropol. 2007; 133(2):808–16. https://doi.org/10.1002/ajpa.20598 PMID: 17405135

Jackson AL, Inger R, Parnell AC, Bearhop S. Comparing isotopic niche widths among and within communities: SIBER–Stable Isotope Bayesian Ellipses in R. J Anim Ecol. 2011; 80(3):595–602. https://doi.org/10.1111/j.1365-2656.2011.01806.x PMID: 21401589

Baied CA, Wheeler JC. Evolution of High Andean Puna Ecosystems: Environment, Climate, and Culture Change over the Last 12,000 Years in the Central Andes. Mt Res Dev. 1993; 13(2):145–56. https://doi.org/10.2307/3673632

Szpak P. Stable Isotope Ecology and Human-Animal Interactions in Northern Peru [Ph.D. Dissertation]. London, Ontario: Western University; 2013.

López M, Cartajena I, Loyola R, Núñez L, Carrasco C. The Use of Hunting and Herding Spaces: Stable Isotope Analysis of Late Archaic and Early Formative Camelids in the Tulan Transect (Puna de Atacama, Chile). Int J Osteoarchaeol. 2017; 27(6):1059–69. https://doi.org/10.1002/oa.2631

Berenguer J, Dauelsberg P. El Norte Grande en la órbita de Tiwanaku. In: Hidalgo J, Chiapacasse V, Berenguer J, Dauelsberg P, editors. Culturas de Chile hasta los Albores de la Conquista. Santiago, Chile: Andrés Bello; 1989. p. 129–80.

Sutter RC. Prehistoric Genetic and Culture Change over the Last 12,000 Years in the Central Andes. Mt Res Dev. 1993; 13(2):145–56. https://doi.org/10.2307/3673632

Uribe M. La Cerámica de Arica 40 Años Después de Dauelsberg. Chungará. 1999; 31(2):189–228.

Uribe M, Aguiero C. Alfarería, textiles y la integración del Norte Grande de Chile a Tiwanaku. Boletín de Arqueología PUCP. 2001; 5:397–426.

Korpiisaari A, Ononin M, Chacama J. A Reevaluation of the Absolute Chronology of Cabuza and Related Ceramic Styles of the Azapa Valley, Northern Chile. Latin Amer Antiq. 2014; 25(4):409–26. Epub 01/20. https://doi.org/10.1111/j.1365-2656.2014.02018.x

Valenzuela D, Cartajena I, Santoro CM, Castro V, Gayo EM. Andean caravan ceremonialism in the lowlands of the Atacama Desert: The Cruces de Molinos archaeological site, northern Chile. Quat Int. 2018. https://doi.org/10.1016/j.quaint.2018.09.016

Santoro CM, Capriles JM, Gayo EM, de Porras ME, Maldonado A, Standen VG, et al. Continuities and discontinuities in the socio-environmental systems of the Atacama Desert during the last 13,000 years. J Anthropol Archaeol. 2017; 46:28–39. https://doi.org/10.1016/j.jaa.2016.08.006
140. Costin CL, Earle T. Status Distinction and Legitimation of Power as Reflected in Changing Patterns of Consumption in Late Prehispanic Peru. Amer Antiq. 1989; 54(4):691–714. https://doi.org/10.2307/280677

141. Yacobaccio H. The Historical Relationship Between People and the Vicuña. In: Gordon IJ, editor. The Vicuña: The Theory and Practice of Community Based Wildlife Management. Boston: Springer; 2009. p. 7–20.

142. Hirth K, Pillsbury J. Redistribution and Markets in Andean South America. Curr Anthropol. 2013; 54(5):642–7. https://doi.org/10.1086/673114

143. Dedenbach-Salazar Saénz S. Inka Pachaq Llamanp a Willaynin . Uso y crianza de los camelídos en la época incaica. Estudio lingüístico y etnohistórico basado en las fuentes lexicográficas y textuales del primer siglo después de la conquista. Bonn: Bonner Americanistische Studien–Estudios Americanistas de Bonn; 1990.

144. Murra JV. El mundo andino: población, medio ambiente y economía. 1. ed. Lima: Instituto de Estudios Peruanos / Pontificia Universidad Católica del Perú; 2002. 511 p.

145. deFrance S. Zooarchaeology in Complex Societies: Political Economy, Status, and Ideology. Journal of Archaeological Research. 2009; 17:105–68. https://doi.org/10.1007/s10814-008-9027-1

146. Miyano JP, Lantos I, Ratto N, Orgaz M. Animales e Incas en el oeste Tinogasteño (Catamarca, Argentina). Latin Amer Antiq. 2017; 28(1):28–45. https://doi.org/10.1017/laq.2016.7

147. Capriles JM, Domic AI, Alconini S. Continuity and change in faunal consumption patterns at the pre-Inka and Inka site of Yoroma, Bolivia. In: Campana D, Crabtree P, deFrance S, Lev-Tov J, Choyke A, editors. Anthropological Approaches to Zooarchaeology: Complexity, Colonialism, and Animal Transformations. Oxford: Oxbow Books; 2010. p. 105–12.

148. D’Altroy TN, Lorandi AM, Williams VI, Calderari M, DeMarrais E, et al. Inka rule in the northern Calchaquí valley, Argentina. J Field Archaeol. 2000; 27(1):1–26. https://doi.org/10.1179/jfa.2000.27.1.1

149. Mengoni Goñalons GL. Camelid hunting and herding in Inca times. In: Albarella U, Russ H, Vickers K, Viner-Daniels S, editors. The Oxford Handbook of Zooarchaeology. Oxford: Oxford University Press; 2017.

150. Stanish C. Nonmarket Imperialism in the Prehispanic Americas: The Inka Occupation of the Titicaca Basin. Latin Amer Antiq. 1997; 8(3):195–216. https://doi.org/10.1086/971652

151. Knudson KJ, Gardella KR, Yaeger J. Provisioning Inka feasts at Tiwanaku, Bolivia: the geographic origins of camelids in the Pumapunku complex. J Archaeol Sci. 2012; 39(2):479–91. https://doi.org/10.1016/j.jas.2011.10.003

152. Boserup E. The Conditions of Agricultural Growth. Chicago, IL: Aldine; 1965.

153. Topic TL, McGreevy TH, Topic JR. A Comment on the Breeding and Herding of Llamas and Alpacas on the North Coast of Peru. Amer Antiq. 1987; 52(4):832–5.

154. Muñoz I, Focacci G. San Lorenzo: testimonio de una comunidad de agricultores y pescadores Postinca de Arauco en el Valle de Azapa (Arica-Chile). Chongará. 1985; 15:7–30.

155. Schiappacasse V, Niemeyer H. Avances y sugerencias para el conocimiento de la prehistoria tardía en la desembocadura del Valle de Camarones. Chongará. 1989; 22:63–84.

156. Carter CP. The Economy of Prehistoric Northern Chile: Case Study Caleta Vítor [Ph.D. Dissertation]. Canberra: Australia National University; 2016.

157. Muñoz I. Investigaciones arqueológicas en los tumbos funerarios del valle de Azapa (Arica). Chongará. 1981; 6:57–95.

158. Muñoz I. Spatial dimensions of complementary resource utilization at Acha-2 and San Lorenzo. In: Aldenderfer MS, editor. Domestic architecture, ethnicity, and complementarity in the south-central Andes. Iowa City: University of Iowa Press; 1993. p. 94–102.

159. Muñoz I, Chacana J. Complejidad Social en las Alturas de Arica: Territorio, Etnicidad y Vinculación con el Estado Inca. Arica: Universidad de Tarapacá; 2006.

160. Schiappacasse V, Niemeyer H. Continuidad y cambio cultural en el poblado actual Colonial e Inca de Pachica, quebrada de Camarones. Chongará. 1997; 29:209–47.

161. Hidalgo J. Pescadores del litoral árido de valles y quebradas del norte de Chile y su relación con agricultores. Siglos XVI-XVII. Historia Andina en Chile. Santiago: Editorial Universitaria; 2004 [1988]. p. 431–69.

162. Urbina S, Figueroa E. La organización económica del Repartimiento de Arica a través de la Tasa la Gasca de 1550 y sus efectos posteriores. Informe Técnico, Año 4. Proyecto FONDECYT N˚ 1151046. 2018.
163. King CL, Millard AR, Gröcke DR, Standen VG, Arriaza BT, Halcrow SE. Marine resource reliance in the human populations of the Atacama Desert, northern Chile--A view from prehistory. Quat Sci Rev. 2018;182:163–74. https://doi.org/10.1016/j.quascirev.2017.12.009

164. King CL, Halcrow SE, Millard AR, Gröcke DR, Standen VG, Portilla M, et al. Let’s talk about stress, baby! Infant-feeding practices and stress in the ancient Atacama desert, Northern Chile. Am J Phys Anthropol. 2018; 166(1):139–55. https://doi.org/10.1002/ajpa.23411 PMID: 29355900

165. Alfonso-Durruty MP, Gayo EM, Standen V, Castro V, Latorre C, Santoro CM, et al. Dietary diversity in the Atacama desert during the Late intermediate period of northern Chile. Quat Sci Rev. 2019; 214:54–67. https://doi.org/10.1016/j.quascirev.2019.04.022

166. Santana-Sagredo F, Hubbe M, Uribe M. Isotopic Evidence for Marine Consumption and Mobility in the Atacama Desert (Quillagua, Northern Chile). Int J Osteoarchaeol. 2016; 26(3):476–89. https://doi.org/10.1002/oa.2437

167. Santana-Sagredo F, Lee-Thorp JA, Schulting R, Uribe M. Isotopic evidence for divergent diets and mobility patterns in the Atacama Desert, northern Chile, during the Late Intermediate Period (AD 900–1450). Am J Phys Anthropol. 2015; 156(3):1042–54. https://doi.org/10.1002/ajpa.23413 PMID: 25386766

168. Pizarro J, Docmac F, Harrod C. Clarifying a trophic black box: stable isotope analysis reveals unexpected dietary variation in the Peruvian anchovy Engraulis ringens. PeerJ. 2019; 7:e6968. https://doi.org/10.7717/peerj.6968 PMID: 31143557

169. De Pol-Holz R, Robinson RS, Hebbeln D, Sigman DM, Ulloa O. Controls on sedimentary nitrogen isotopes along the Chile margin. Deep Sea Res Part 2 Top Stud Oceanogr. 2009; 56(16):1042–54. https://doi.org/10.1016/j.dsr2.2008.09.014

170. Pestle WJ, Torres-Rouff C, Gallardo F, Ballester B, Clarot A. Mobility and Exchange among Marine Hunter-Gatherer and Agropastoralist Communities in the Formative Period Atacama Desert. Curr Anthropol. 2015; 56(1):121–33. https://doi.org/10.1086/679594

171. Arriaza BT, Standen VG, Belmonte E, Rosello E, Nials F. The peopling of the Arica coast during the preceramic: A preliminary view. Chungara Revista de Antropología Chilena. 2001; 33:31–6. https://doi.org/10.4067/S0717-73562001000100005

172. Page HM. Variation in the natural abundance of 15N in the halophyte, Salicornia virginica, associated with groundwater subsidies of nitrogen in a southern California salt-marsh. Oecologia. 1995; 104 (2):181–8. https://doi.org/10.1007/BF00328583 PMID: 28307355

173. Tieszen LL, Chapman M. 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. Santa Cruz de Tenerife: Museo Arqueológico y Etnográfico de Tenerife; 1992. p. 409–25.

174. Murra JV. Cloth and Its Functions in the Inca State. Amer Anthropol. 1962; 64(4):710–28.

175. Millaire J-F. Woven identities in the Virú Valley. In: Millaire J-F, Morlon M, editors. Gallinazo: An Early Cultural Tradition on the Peruvian North Coast. Los Angeles: Cotsen Institute of Archaeology Press; 2009. p. 149–65.

176. Rowe AP, Benson EP, Schaffer A-L, editors. The Junius B. Bird Pre-Columbian Textile Conference, May 19th and 20th, 1973. Washington, D.C.: The Textile Museum; 1979.