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Assessing Prehispanic Herding Strategies through Stable Isotope Analysis: A Case Study from the Dry Puna of Argentina

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ABSTRACT

The main goal of this work is to study the camelid herding and management strategies employed by the human groups that occupied the Dry Puna of Argentina during the late Holocene. Carbon and nitrogen stable isotope compositions were measured on bone collagen from domesticated South American camelids (llamas: *Lama glama*) recovered at two archaeological sites (Huirunpure and Chayal Cave). These results were interpreted using an already published data set of $\delta^{13}C$ and $\delta^{15}N$ values measured on bone collagen from modern herds of llamas managed in a traditional way. Our results showed that even though the archaeological sites of Huirunpure and Chayal Cave are located within different settings – at 4020 and 3700 masl respectively – and present different chronologies – 0–650 and 1300–1500 CE respectively – the llamas from both sites exhibit similar $\delta^{13}C$ and $\delta^{15}N$ values. This pattern was explained considering the characteristics of the vegetation communities that grow in the vicinity of both sites as well as the paleoenvironmental records of the Andean highlands. In sum, this work presents and discusses some preliminary results on the study of prehispanic herding practices in the Dry Puna of Argentina during the first 1500 years of the Common Era through stable isotope analysis.

Introduction

Human subsistence and resource management strategies are often considered as linked to and limited by the properties of the surrounding habitat, such as regional climate or geomorphology (Schutkowski 2006). Particularly in arid and semi-arid highland environments, these properties often involve reduced precipitation, extended periods of drought, and low biological productivity (Laity 2009). In such scenarios, pastoralism, understood as the breeding and herding of domesticated livestock, can be thought of as an adaptive strategy to cope with low primary productivity and buffer climate instability given its capacity to transform grass and shrub plants, which are often unpalatable to humans, into consumable energy and valuable animal products (Butt 2010).

Nowadays, traditional herders are distributed among different areas of Africa, Eurasia, the Middle East and the Andean highlands in South America (Khazanov 1994). These indigenous pastoralist groups organise themselves through a variety of subsistence and mobility strategies, reflecting the particular environmental, cultural and historical trajectories that shape their practices in both local and regional scales (Makarewicz 2013).

In the Andean highlands of South America, modern husbandry involves the herding of domesticated South American camelids such as llamas (*Lama glama*) and alpacas (*Lama pacos*), caprines such as sheep and goats, and cows. Caprines and cows were introduced from Europe in the sixteenth century, whereas both llamas and alpacas were domesticated within the Central and South-Central Andes. The archaeological evidence suggests that camelid domestication took place *ca.* 4000–2500 BCE, enabling ongoing access to diverse animal products – meat, fibre, dung – as well as the development of long-distance exchange networks through llama caravan trade (Mengoni Goñalons and Yacobaccio 2006). In this sense, it has been proposed that while the stable and arid conditions of the mid-Holocene set an appropriate scenario for camelid domestication (Yacobaccio 2001, 2006), the more humid but unstable conditions of the late Holocene led to the development of pastoralism as the predominant subsistence strategy in areas such as the Dry Puna of Argentina (Morales et al. 2009). Nevertheless, few works have addressed how the local herders established their herding strategies and their use of the landscape within this highly variable environmental scenario, while the specific characteristics of camelid pastoralism in terms of the diet and the mobility of llama herds remain largely unexplored to this day. In this sense, we consider it is necessary to address the particular characteristics of the animal management practices

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employed by the human groups that occupied the Dry Puna during the late Holocene.

Several studies have explored the potential of stable isotope analysis to investigate prehistoric herding strategies and their relationship to environmental change in various parts of the globe (Balasse et al. 2002; Britton, Müldner, and Bell 2008; Towers et al. 2011, among others), addressing issues such as mobility and foddering, which usually escape the scope of zooarchaeological studies (Makarewicz 2016). Many of these studies employ modern animal isotopic data as comparative datasets in order to explore variation in the isotopic compositions of archaeofaunal remains (Thornton et al. 2011) and to posit models to test archaeological hypotheses (Balasse and Ambrose 2005). Others emphasize the importance of building an isotopic ecology for the study area in order to address the main causes of variation in the isotopic values of the archaeofaunal materials analysed (Szpak et al. 2016). Particularly, carbon and nitrogen stable isotope compositions measured on bone collagen of zooarchaeological materials from the Puna highlands have proved useful to study temporal changes in camelid diet as well as the location of the pasturelands used by prehistoric herders (Grant and Olivera 2016; Grant, Mondini, and Panarello 2018; López et al. 2017; López, Cartajena, and Núñez 2013; Samec, Morales, and Yacobaccio 2014; Yacobaccio, Samec, and Catá 2010; among others).

This article aims to explore the characteristics of the herding strategies employed by the pastoralist groups that inhabited the Dry Puna of Argentina during the late Holocene through stable isotope analysis. Carbon and nitrogen stable isotope compositions ($\delta^{13}C$ and $\delta^{15}N$ values) were measured on bone collagen extracted from zooarchaeological materials assigned to llamas and recovered at two pastoralist sites from the Susques area, Huirunpure and Chayal Cave (Jujuy Province, Argentina). These sites are located at different geographical settings and cover a time span from 0 to 1500 CE, which delimits different local characteristics dictated by their differences in altitude, climate, and chronology, all aspects that will be explored in our analysis. At the same time, the data generated here is compared to the isotopic values measured on bone collagen from modern domesticated camelids from the same area previously published by Samec, Yacobaccio, and Panarello (2018), in order to shed new light over questions such as prehispanic herd management, camelid diet and pastoralist mobility.

Study Area: The Dry Puna of Argentina

The Puna of Argentina constitutes the eastern sector of the Puna of Atacama and is located between 22° and 27° S and between 3000 and 5000 masl (Figure 1). It is characterised as a highland desert that contains several NE–SW oriented mountain ranges. It presents a wide daily temperature range, high solar radiation and low atmospheric pressure (Buitrago and Larrán 1994). Due to water scarcity, primary productivity is concentrated in a few stable hydrological systems such as primary basins, high ravines, and wetlands (Dollfus 1991). The only sources of freshwater are a few rivers and several springs scattered throughout the landscape. Precipitation occurs during summer, governed by the South American monsoon system that results in about 80% of the annual rainfall falling between December and March (Zhou and Lau 1998). Additionally, precipitation exhibits a latitudinal gradient that delimits two sub-regions within the Puna of Argentina: the Dry Puna, located north of 25° S, with a mean annual precipitation of 300 mm/year; and the Salt Puna, located south of 25° S, with a mean annual precipitation that barely reach 100 mm/year (Bianchi, Yañez, and Acuña 2005).

Within the Dry Puna, vegetation communities are arranged according to altitude and its effects on humidity and temperature (Cabrera 1976) and present different proportions of C_3 and C_4 plants (Samec, Yacobaccio, and Panarello 2017). The shrub-steppe (*tolar*) is located between 3500 and 3900 masl and includes mainly C_3 shrubs and grasses and some C_4 grasses. Mixed steppes are located between 3900 and 4100 masl and represent ecotonal landscapes composed of grasses and shrubs in which mainly C_3 plant species are represented. The grass-steppe (*pajonal*) is located between 4100 and 4700 masl and includes predominantly C_3 plant species. Finally, wetlands (*vegas*) are scattered along the landscape between 3500 and 4700 masl and represent restricted patches with high grass cover all year round.

Environmental Scenarios in the Dry Puna During the Late Holocene

The environmental conditions that now characterise the study area have changed several times during the Holocene, setting important challenges to human groups since the peopling of the Andean region during the Pleistocene-Holocene transition. Particularly, the onset of the late Holocene *ca.* 2000 BCE in the Andean highlands can be described as a transition towards colder and more humid conditions than the preceding mid-Holocene (Abbott et al. 2003; Thompson et al. 1998; Thompson, Mosley-Thompson, and Henderson 2000). However, summer precipitation levels in the region varied significantly over the past 3000 years. This variability has been explained by the complex interplay of short-term changes in the intensity and frequency of the El Niño Southern Oscillation (ENSO) (Kanner et al. 2013) and centennial-scale variations in the North Hemisphere temperatures and the Pacific sea surface temperature gradient (Vuille et al. 2012).
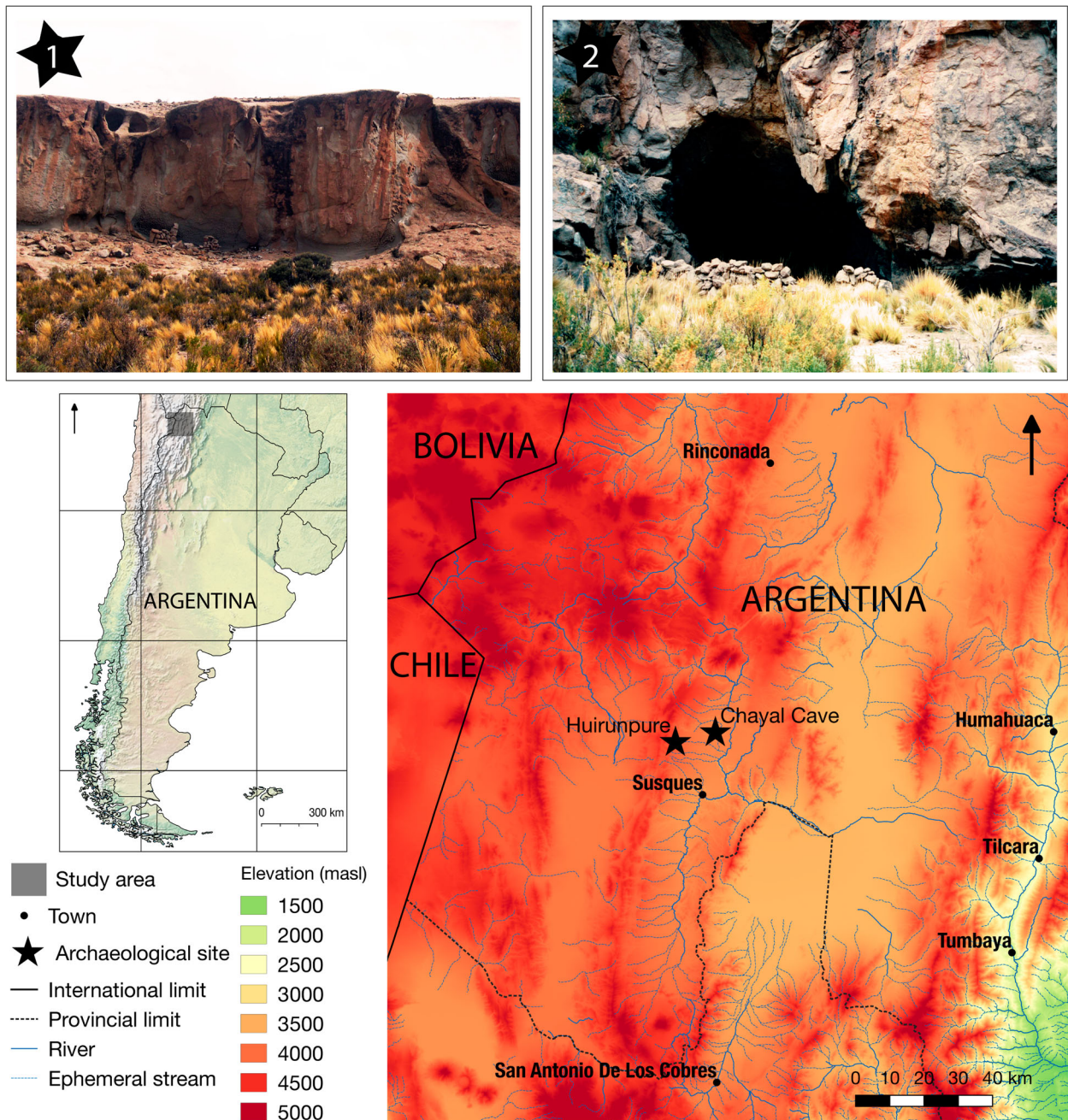
Figure 1. The archaeological sites of (1) Huirunpure and (2) Chayal Cave and their location within the study area. Altitudinal ranges are represented in the map at the bottom left corner. Maps were elaborated using QGIS software and standardised sheets available at ign.gob.ar.

Although pronounced short-term environmental instability has been the main feature of the Andean highlands over the past few millennia, three prominent mean-state changes have been detected in high resolution records such as the $\delta^{18}O$ series from the Quelccaya ice core (Thompson et al. 2013) and Pumacocha lake calcite deposits (Bird et al. 2011). Higher $\delta^{18}O$ values, indicative of warmer and drier conditions for the area, can be found at Quelccaya from at least 1100 to 1300 CE (Thompson et al. 2013) and even earlier in Pumacocha at 900 to 1100 CE (Bird et al. 2011), which has been interpreted as an expression of the Medieval Climate Anomaly (MCA). Similar conditions have been described for the Current Warm Period

(CWP) beginning at *ca.* 1880 CE. In between these two warm and dry periods, the Little Ice Age (LIA) shows the lowest $\delta^{18}O$ values, indicating a cool, wet phase starting as early as 1300 CE at Pumacocha, with minimum values during the time-span between 1400 and 1820 CE (Bird et al. 2011). Similarly, the LIA record at Quelccaya consists of significantly lower $\delta^{18}O$ values from ~1520 to 1880 CE (Thompson et al. 2013).

Due to the paucity of information available on the late Holocene in the Argentine Puna, regional paleoenvironmental records such as the ones described above are commonly used to discuss climate and environmental change in local settings. However, over the

last few years, a growing body of research conducted in the Dry Puna of Argentina has provided some insights regarding the impact of regional climate change on local environments. In this sense, highly variable humidity conditions have been reported for the last few millennia at Barrancas (Pirola et al. 2018), Pastos Chicos (Tchilinguirian et al. 2014), Lapao (Oxman et al. 2015; Tchilinguirian et al. 2014) and Cerro Tuzgle (Schittek et al. 2016). Particularly, the high-resolution Cerro Tuzgle peat archive points to the existence of a short period between 50 BCE and 100 CE characterised by increased aridity and higher temperature, followed by a more humid phase that lasted until 550 CE (Schittek et al. 2016). In contrast, short-term variability in humidity might have increased between 550 and 1100 CE according to this record (Schittek et al. 2016). At the same time, evidence of a dry phase compatible with the MCA chronology (900–1500 CE) has been found in Laguna Pululos, with maximum aridity recorded between 1360 and 1460 CE (Morales, Bustos, and Maidana 2015). In turn, the LIA is represented in Laguna Pululos from 1500 to 1900 CE, albeit with certain internal variability (Morales, Bustos, and Maidana 2015). Particularly in Quebrada Lapao, a humid phase is detectable from 1538 to 1665 CE, followed by a drier period (Oxman et al. 2015); these phases were identified as the early and late LIA phases described by Thompson et al. (2013).

Herding Practices in the Dry Puna from a Diachronic Perspective

South American camelids represent the only large herd mammals that were domesticated in the Americas and have been an important resource for prehistoric, historic, and modern Andean societies (Mengoni Goñalons and Yacobaccio 2006; Moore 2016, among others). Currently, four species are recognised: two wild, the vicuña (*Vicugna vicugna*) and the guanaco (*Lama guanicoe*), and two domesticated, the llama (*Lama glama*) and the alpaca (*Lama pacos*) (Wheeler 1995). Since there is no conclusive evidence of alpaca herding during prehispanic times in the Puna highlands of Argentina (Mengoni Goñalons and Yacobaccio 2006), our research will focus on the study of llama herding strategies.

Recent investigations carried out in different areas of the South-Central Andes have provided convincing evidence to support the existence of a local process of llama domestication within the Puna of Atacama (Yacobaccio and Vilá 2016). These evidences include: the appearance of llama-size individuals since 4000 BCE (Yacobaccio et al. 2013), the presence of bone pathologies associated to captivity since 2700 BCE (Cartajena, Núñez, and Grosjean 2007), and the occurrence of corrals and pens as early as 2600 BCE (Aschero and Yacobaccio 1998–

1999), among others (for details see Mengoni Goñalons and Yacobaccio 2006; Yacobaccio 2001; Yacobaccio and Vilá 2016).

Within the Dry Puna of Argentina, the initial developing of llama herding practices becomes evident *ca.* 800 BCE, as shown by the large quantity of llama-size bones recovered at the sites of Huirunpure and Quispe Cave as well as the presence of artefacts made from llama fibre within the burial of Morro del Ciénego Chico (Yacobaccio et al. 1997–1998). Around 900 CE, pastoralist production intensified, and herding became the predominant subsistence strategy within the area, as inferred from the materials recovered at the archaeological sites of Chayal Cave and Hornillos 3 (Yacobaccio et al. 2011). During the following period, pastoralist intensification promoted a diversified use of llama herds to obtain both primary and secondary products as well as the development of long-distance exchange networks using large-size llamas as pack-animals (Mengoni Goñalons and Yacobaccio 2006).

Nowadays, traditional llama husbandry in the Dry Puna of Argentina is mostly oriented towards the production of fibre and meat (Yacobaccio 2007). The herds are fed on natural pastures, while mobility is practiced in order to avoid overgrazing of the pasturelands managed by each household. As a consequence of this mobility strategy, the settlement pattern is dispersed over the landscape, comprising sites that are used differentially during the annual cycle (Yacobaccio, Madero, and Malmierca 1998). Two types of settlements can be distinguished: residential bases (*casas*) and temporary sites (*estancias*) (Yacobaccio 2007). Residential bases are usually located near water sources or *vegas* and constitute complex structures with many rooms (Yacobaccio, Madero, and Malmierca 1998). Particularly in the Susques area, the herders and their animals stay at the residential base for more than eight months a year, making use of the pastures that grow in the vicinity of the settlement. In contrast, a part of the family group and their animals occupy temporary sites for two to three months during the winter, herding their llamas at the different plant communities located near these sites. These temporary sites are smaller, usually composed of a single room and a corral made of *pirca* or shrub walls (Yacobaccio, Madero, and Malmierca 1998). In this sense, the use of these different settlements follows a seasonal pattern and determines the access to different pastures to be included in the diet of the herds. Nevertheless, and despite this mobility strategy, carbon and nitrogen stable isotope compositions measured on modern llamas' bone collagen represent an average of the vegetational assemblages consumed, where clearly those plants that grow in the vicinity of the residential base present a prevailing role (Samec 2014).

Isotopic Background and Expectations

Carbon stable isotope composition of bone collagen from herbivorous ungulates is influenced by the distribution of C_3 and C_4 plants and their relative abundances, as well as human intervention in feeding habits and mobility in the case of domesticated animals (Koch, Fogel, and Tuross 1994). In this sense, several studies have identified a negative correlation between altitude and $\delta^{13}C$ values measured on modern camelids' bone collagen within the Dry Puna of Argentina (Fernández and Panarello 1999–2001; Samec, Yacobaccio, and Panarello 2018; Yacobaccio, Morales, and Samec 2009) and other Andean areas (Dufour et al. 2014; Szpak et al. 2014; Thornton et al. 2011), which has been explained by the distribution of C_3 and C_4 plants according to altitude (Szpak et al. 2013). Particularly, studies performed within our study area have revealed that C_4 plants are only present at lower elevations due to increased temperature and water stress, and practically disappear above a certain threshold – around 3900 masl depending on the specific area – where these conditions are no longer found (Samec, Yacobaccio, and Panarello 2017).

On the other hand, variations in the $\delta^{15}N$ values measured on bone collagen from herbivorous animals can be related to the influence of variables like temperature and water availability in soil and plant $\delta^{15}N$ values (Murphy and Bowman 2006). In this sense, a negative correlation between altitude and $\delta^{15}N$ values of modern camelids' bone collagen has also been identified within the study area (Samec, Yacobaccio, and Panarello 2018) as well as in several areas of the Central Andes (Szpak et al. 2014; Thornton et al. 2011), a pattern that has been explained considering that plant $\delta^{15}N$ values vary according to precipitation and temperature gradients related to altitude variation (Samec, Yacobaccio, and Panarello 2017; Szpak et al. 2013).

Therefore, and taking into account these previous patterns, we expect the $\delta^{13}C$ and $\delta^{15}N$ values measured on bone collagen extracted from the llama remains recovered at Huirunpure and Chayal Cave to exhibit at least two dimensions of variation. One related with the altitudinal location of the sites and its influence on the mean $\delta^{13}C$ and $\delta^{15}N$ values of the vegetal communities available for consumption, and another related to the chronology of the occupational levels analysed here, which might have determined differences in the environmental scenarios related to climate change and its possible effects on the distribution of C_3 and C_4 plants and on nitrogen cycling. However, due to the high-frequency nature of environmental variability during the late Holocene within our study area, we expect $\delta^{15}N$ values to be more sensitive to changes in temperature or humidity than $\delta^{13}C$ values. In this sense, carbon stable isotope compositions in animal bone collagen are determined not only by the proportions of C_3 and C_4 plants available within the assemblages but also by camelid feeding preferences, and would probably have presented certain stability in the face of short-term variations in temperature and humidity (Samec, Morales, and Yacobaccio 2014). Overall, if these two dimensions of variation cannot account for the observed patterns in the carbon and nitrogen stable isotope compositions presented here, a third dimension may be considered, one related to the particular characteristics of the herding practices within the Dry Puna of Argentina during prehispanic times. In this sense, a comparison of the $\delta^{13}C$ and $\delta^{15}N$ values of archaeological llamas with the $\delta^{13}C$ and $\delta^{15}N$ values of modern ones from similar settings will allow us to discuss the extension of the ranges of herding mobility – whether they included other plant assemblages with varying compositions of C_3-C_4 plants and different $\delta^{15}N$ mean values – and/or the existence of long-distance trade networks that connected different areas through llama caravans – possibly involving the consumption of different proportions of C_3-C_4 plants with different $\delta^{15}N$ mean values.

The Archaeological Sites: Huirunpure and Chayal Cave

Huirunpure

The site of Huirunpure is located in a ravine called Agua Chica at the eastern flanks of the Taire mountain range within the Susques Department in the Province of Jujuy, Argentina (Figure 1). The site is a rockshelter, located at 4020 masl and surrounded by mixed steppe vegetation. The rockshelter has a total surface of 139 m² and presents three structures (S1, S2, and S3) and a discard area (Yacobaccio et al. 1997–1998). Two of these structures have been excavated and their radiocarbon dates are comprised within 2040 and 690 years BP (0–1370 CE) (Yacobaccio et al. 1997–1998). The excavations carried out within the site recovered an obsidian projectile point and other lithic tools, a silver medal, malachite, and shell beads from the Pacific Ocean, as well as a well preserved bone assemblage. In this article, we will analyse the zooarchaeological materials recovered in S1 (NISP = 505), specifically in the layers 1 and 2, dated on 1470 and 2040 years BP respectively (*ca*. 0–650 years CE), which were published in detail by Yacobaccio et al. (1997–1998) (Table 1). The bone assemblage recovered within these contexts is extremely well preserved – only 2% of the bones are affected by weathering in stages above 2 according to Behrensmeyer (1978) – and is not affected by density-mediated destruction – there is no correlation between frequency and structural density of the anatomical parts identified – (Yacobaccio et al. 1997–1998). Within the specimens identified in a taxonomic level, camelids are the most abundant

and they represent the 67% of the assemblage, of which 50% was identified as corresponding to the domesticated species *L. glama* based on osteometric analyses (Yacobaccio et al. 1997–1998). Considering the age classes represented within the domesticated camelid bone assemblage, adult individuals represent 75% of the bones, followed by juveniles with 15% and newborns with only 10%. This age structure is similar to the one found in modern pastoralist sites within the Susques area, given the high percentage of adults retrieved in the ethnoarchaeological survey of the bone assemblages from discard areas (Yacobaccio and Madero 2001). Overall, the archaeological site of Huirunpure can be defined as a temporary settlement of llama herders that participated in long-distance exchange networks.

Chayal Cave

The site of Chayal is located in the Chayal ravine, 3 km away from the small town of San Juan de Quillaques, within the Susques Department in the Province of Jujuy, Argentina (Figure 1). This ravine is characterised by a very sharp topography and therefore remains protected from the wind, and a small creek flows within it. The archaeological site is surrounded by an unusually high proportion of grasses – such as *Stipa* sp. and *Festuca* sp. – and a low proportion of shrubs. The cave itself is located at an altitude of 3700 masl and has a total surface of 20 m^2 from which only 4.5 m^2 were excavated and five natural layers bearing three occupational levels were identified. Two of these occupational levels were radiocarbon dated and their chronology is comprised within 1080 and 410 years BP (*ca.* 1000–1500 CE) (Yacobaccio et al. 1997–1998). One of the radiocarbon dates of the layer 3 (410 ± 50 years BP) comes from a hearth excavated on the cave floor and surrounded by slabs, whereas the earlier date (680 ± 50 years BP) comes from charcoal fragments found scattered within the layer (Table 1). On this matter, we consider that the chronology of the human occupation is closer to the most recent date since the radiocarbon date sample was obtained from a more reliable context. Overall, the excavations recovered well preserved bone remains accompanied by undecorated ceramic sherds – probably linked to the 'Yavi complex' – and some lithic instruments. This cave is adjacent to a larger site, Chayal 2, which comprises seven habitation structures, corrals and storage facilities. Chayal Cave was possibly linked to this main site, acting as a special activity area. In this case, layer 3 was selected to conduct the analyses carried out within this work, since it accounts for 84% of the total bone specimens recovered at the site (NISP = 1291). The bone assemblage has little signs of weathering – only 4% of the assemblage presents weathering stages above 2 according to the scale of Behrensmeyer

(1978) – and is not affected by density-mediated attrition – frequency and structural density of the anatomical parts recovered are not correlated – (Yacobaccio et al. 1997–1998). Within the animal species present at the site, viscachas (*Lagidium* sp.) predominate with a 50% of the assemblage, followed closely by camelids, which represent 38% of the total number of identified specimens. Regarding the age profile, 45% of the camelid bones correspond to adult individuals, 33% to newborns and 21% to juveniles. This age structure is somewhat different from the one registered in modern pastoralist contexts within the study area, an aspect that could be related to the importance of hunting strategies during the occupation of the site. Nevertheless, the osteometric analysis of the camelid bones resulted in their identification as *L. glama* (Yacobaccio et al. 1997–1998).

Materials and Methods

A total of 18 bone specimens from both archaeological sites were selected to carry out the collagen extraction process. Sample selection considered the following criteria: stratigraphic location – layer and grid – , skeletal part and laterality – in order to avoid the measuring of the same individual – , taxonomy – specimens osteometrically assigned to *Lama glama* – , age – according to bone fusion and dental eruption and wear patterns established by Kent (1982) and Wheeler (1982) – , preservation – weathering stage below 3 following Behrensmeyer (1978) – , and tissue – preferentially diaphysis of compact bones. Whenever possible the same skeletal parts were chosen, whereas in those cases when this was not possible age and fusion stage were considered in order to avoid duplicate specimens.

Samples were pre-treated and measured at INGEIS (Instituto de Geocronología y Geología Isotópica, Buenos Aires, Argentina). All bone samples were prepared following the collagen extraction method developed by Tykot (2004) with some modifications (Samec, Yacobaccio, and Panarello 2018). Measurements of $\delta^{13}C$ and $\delta^{15}N$ values for each sample were conducted using a CarloErba Elemental Analyzer (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 calibrated against VPDB and AIR reference standards for carbon and nitrogen (Coplen, Krouse, and Böhlke 1992; Craig 1957). Replicates of internal standards showed analytical errors (SD) to be on the order of ± 0.2 ‰ for both $\delta^{13}C$ and $\delta^{15}N$ values.

Results

Here we present 18 new $\delta^{13}C$ and $\delta^{15}N$ values measured on bone collagen of llamas recovered at the archaeological sites of Huirunpure (*n* = 10) and Chayal

Table 1. δ^{13}C and δ^{15}N values measured on bone collagen from llamas recovered at Chayal Cave and Huirunpure. Radiocarbon dates, already published by Yacobaccio et al. 1997–1998, were calibrated with CALIB software using the Southern Hemisphere calibration curve (Stuiver and Reimer 1993). * Samples excluded from further analysis due to their C:N ratios.

Site	Layer	Radiocarbon Dates (years BP)	Calibrated Dates ± 1 σ (years BCE/CE)	Lab Code	Skeletal Part	δ^{13}C ‰	δ^{15}N ‰	C:N
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	25826	metapodial	−18.3	+8.2	3.4
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	25827	femur	−17.2	+8.6	3.3
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	25828	first phalanx	−18.4	+6.6	3.3
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	25829	femur	−17.3	+7.5	3.3
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	27359	tibia	−18.2	+9.5	3.2
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	27360	humerus	−17.7	+9.4	3.3
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	27361	femur	−17.5	+8.8	3.3
Chayal Cave	3	680 ± 50 and 410 ± 50	1273–1311 and 1453–1511 CE	27362	radius	−17.4	+8.5	3.3
Huirunpure	1	1470 ± 40	598–650 CE	20714	long bone fragment	−18.0	+7.9	3.2
Huirunpure	1	1470 ± 40	598–650 CE	33541	radius	−17.9	+9.8	3.4
Huirunpure	1	1470 ± 40	598–650 CE	33542	radius	−17.4	+6.6	3.3
Huirunpure	1	1470 ± 40	598–650 CE	33543	radius	−18.8	+8.3	4.0*
Huirunpure	1	1470 ± 40	598–650 CE	33544	radius	−18.3	+9.6	3.6
Huirunpure	1	1470 ± 40	598–650 CE	33545	tibia	−18.3	+9.0	3.4
Huirunpure	2	2040 ± 70	71 BCE – 76 CE	20704	long bone fragment	−17.2	+9.1	3.2
Huirunpure	2	2040 ± 70	71 BCE – 76 CE	33547	metacarpal	−17.4	+7.9	3.2
Huirunpure	2	2040 ± 70	71 BCE – 76 CE	33548	radius	−18.9	+5.5	3.7*
Huirunpure	2	2040 ± 70	71 BCE – 76 CE	33549	mandible	−17.3	+6.9	3.3

Cave ($n = 8$), both located in the Dry Puna of Argentina. In order to confirm that the isotopic compositions measured here were not affected by contamination or degradation processes, we considered two criteria: collagen yield – above 1% – and atomic C:N ratio – between 2.9 and 3.6 – (Ambrose 1990; DeNiro 1985; Van Klinken 1999). As a result, two samples from Huirunpure (33543 and 33548) were excluded from further analysis, leaving a total of eight δ^{13}C and δ^{15}N values from this site to be considered (Table 1).

In sum, the δ^{13}C values from the two sites range from -18.4‰ to -17.2 ‰ with a mean value of -17.7 ‰, whereas the δ^{15}N values range from + 6.6 ‰ to + 9.8 ‰ with a mean value of + 8.4 ‰. The δ^{13}C values from Huirunpure range between −18.3 ‰ and −17.2 ‰ with a mean of -17.7 ‰ and a SD of 0.5 ‰, The δ^{13}C values from Chayal range between -18.4 ‰ and -17.2 ‰ with a mean of -17.7 ‰ and a SD of 0.5 ‰. On the other hand, the δ^{15}N values from Huirunpure range between + 6.6 ‰ and + 9.8 ‰ with a mean of + 8.3 ‰ and a SD of 1.2 ‰. And the δ^{15}N values from Chayal range between + 6.6 ‰ and + 9.8 ‰ with a mean of + 8.4 ‰ and a SD of 1.0 ‰.

Both sites present similar δ^{13}C and δ^{15}N values, exhibiting no statistically significant differences when compared (δ^{13}C values: Mann–Whitney Test $U = 30$, $z = -0.16$, $p = 0.87$, and δ^{15}N values: Mann–Whitney Test $U = 30.5$, $z = -0.11$, $p = 0.92$) (Figure 2). At the same time, both the δ^{13}C and the δ^{15}N values from the three layers considered here – i.e. Huirunpure's layers 1 and 2, and Chayal's layer 3 – do not present significant differences when compared (δ^{13}C values: Kruskal–Wallis test $H = 4.49$, $p = 0.10$ and δ^{15}N values: Kruskal–Wallis test $H = 0.75$, $p = 0.69$).

Discussion

Our results show that bone collagen δ^{13}C and δ^{15}N values measured on llama remains recovered at the pastoralist sites of Huirunpure and Chayal Cave, both located in the Dry Puna of Argentina, do not exhibit significant differences despite the fact that the sites are located at different altitudinal settings – i.e. surrounded by different vegetal assemblages – and present different chronologies – i.e. related to different environmental scenarios.

Taking into account the first dimension of variability, the δ^{13}C and δ^{15}N values from both sites are not correlated with altitude ($r = 0.03$ $p = 0.92$ and $r = -0.02$ $p = 0.95$ respectively), contrary as expected from the results previously obtained from modern camelids within the study area (Fernández and Panarello 1999–2001; Samec 2014; Samec, Yacobaccio, and Panarello 2018; Yacobaccio, Morales, and Samec 2009). In order to understand the significance of the differences between our expectations based on the correlation of modern isotopic values with altitude and the results
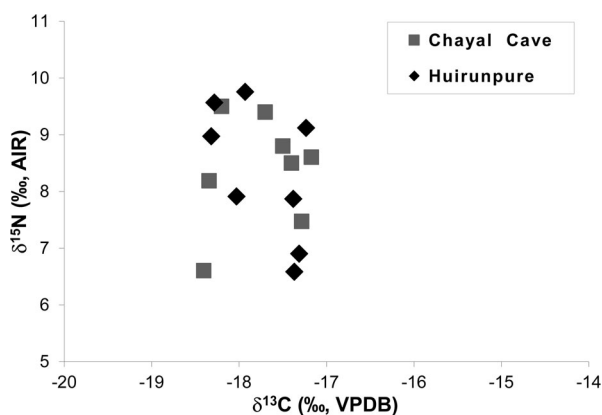

Figure 2. Bone collagen δ^{13}C and δ^{15}N values measured on *Lama glama* specimens recovered in the archaeological sites of Chayal Cave (3700 masl) and Huirunpure (4020 masl).

presented here, we plotted the mean δ^{13}C and δ^{15}N values for both archaeological sites against the linear regression models elaborated based on modern llamas δ^{13}C and δ^{15}N values and their correlation to altitude published by Samec, Yacobaccio, and Panarello (2018). Particularly in this case we calculated and added 95% prediction intervals using R statistical software as a mean to establish if the dispersion of the δ^{13}C and δ^{15}N values of Huirunpure and Chayal can be explained by these models. It is important to point out that in this case the modern δ^{13}C values were adjusted by + 1.5 ‰ to account for the fossil fuel effect and compare them with the δ^{13}C values measured on archaeological materials (Marino and McElroy 1991).

Thus, considering the mean and SD of the archaeological δ^{13}C values, we can see that both Chayal Cave and Huirunpure fall within the 95% prediction interval calculated by the modern linear regression model according to their altitudinal setting (model published by Samec, Yacobaccio, and Panarello 2018) (Table 2). In the case of the llamas from Huirunpure, their mean δ^{13}C value is exactly as predicted by the regression model, indicating that these herds ingested a diet with nearly identical proportions of C_3 and C_4 plants than the one ingested by modern llamas from the same altitudinal setting (Figure 3). Although human occupations in Huirunpure probably occurred during an arid phase (see below for a more detailed discussion), it is likely that this aridity was not sufficiently intense or lasting to generate significant change in C_3 and C_4 proportions of the surrounding pastures (see Samec, Morales, and Yacobaccio 2014 for an example on this). On the other hand, although the mean δ^{13}C values from the llamas of Chayal Cave are comprised within the prediction interval, these values are somewhat lower than expected ($\sim$ 1.2 ‰), suggesting a slightly greater proportion of C_3 plants in the diet than their modern counterparts (Figure 3). In this

case, the particular setting where Chayal Cave is located might contribute to explain this pattern. In fact, the ravine of Chayal is enclosed by steep slopes and today exhibits an unusually high moisture availability, where the proportion of C_3 plants such as *Stipa* sp. and *Festuca* sp. is greater than expected from altitude alone – *i.e.* the domain of the shrub-steppe. The only way out of the ravine is to climb the slopes to access the plateau 150–200 m above, where the main vegetation community is the mixed steppe. Moreover, the most reliable date for the human occupation of Chayal Cave – *i.e.* 410 years BP (1453–1511 CE) from the hearth excavated within layer 3 (see above) – coincides with evidences that point to a humid regional climate, an aspect that could have favoured the development of particularly humid conditions within the ravine and the abundance of C_3 plants in the vicinity of the site during this time. In this sense, the chronology of Chayal's layer 3 shows a lower δ^{18}O mean value in the Quelccaya data series and a higher net accumulation than the series average, aspects that could be explained by the increased humid conditions of the beginning of the Little Ice Age. At the same time, local paleoenvironmental records in the Dry Puna of Jujuy, such as the Laguna Pululos core, support the existence of a humid period beginning at *ca.* 1500 CE in the area (Morales, Bustos, and Maidana 2015). Thus, based on the environmental characteristics inferred for the immediate surroundings of Chayal Cave at the time, we can postulate that herders moved with their herds in and out of the ravine, combining the use of different pasturelands with significant amounts of C_3 plants available.

On the other hand, the δ^{15}N mean and SD values from both archaeological sites present a different picture when plotted against the linear regression model built based on the δ^{15}N values measured on modern llamas from the same area (model published by Samec, Yacobaccio, and Panarello 2018) (Figure 4). In both cases, the mean values are higher than expected, even though almost all the Chayal values
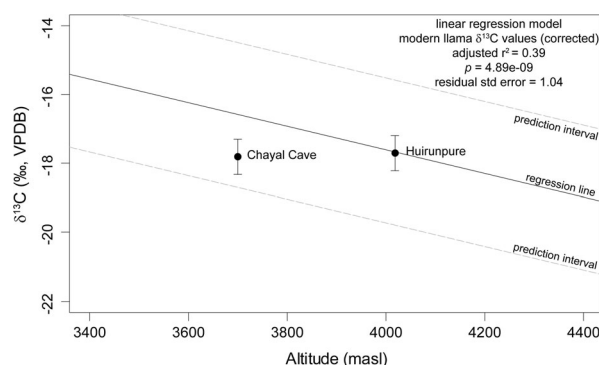
Table 2. 95% prediction intervals for altitudes of 3700 and 4020 masl based on the regression models built with modern llama δ^{13}C and δ^{15}N values vs. basic statistics of the δ^{13}C and δ^{15}N values from Chayal Cave (3700 masl) and Huirunpure (4020 masl).

Predictions based on the modern regression models			Summary statistics for the archaeological sites		
	Altitude 3700	Altitude 4020		Chayal Cave	Huirunpure
δ^{13}C ‰					
Fit	−16.60	−17.70	Mean	−17.8	−17.7
Lower limit	−18.69	−19.79	Minimum	−18.4	−18.3
Upper limit	−14.51	−15.60	Maximum	−17.2	−17.2
δ^{15}N ‰					
Fit	+7.58	+6.23	Mean	+8.4	+8.3
Lower limit	+5.81	+4.46	Minimum	+6.6	+6.6
Upper limit	+9.35	+8.00	Maximum	+9.5	+9.8

Figure 3. Mean and SD for δ^{13}C values from the sites Chayal Cave (3700 masl) and Huirunpure (4020 masl) plotted against the linear regression model for modern llama δ^{13}C values published by Samec, Yacobaccio, and Panarello (2018).
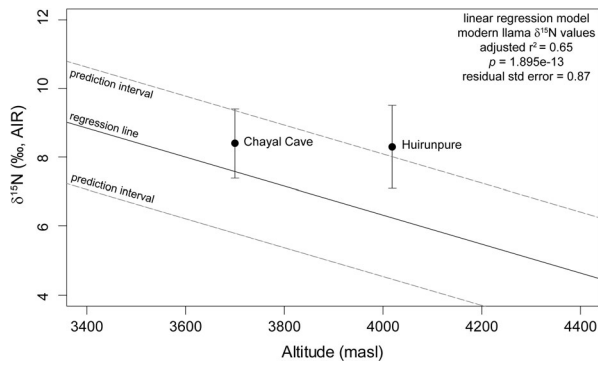
Figure 4. Mean and SD for $\delta^{15}N$ values from the sites Chayal Cave (3700 masl) and Huirunpure (4020 masl) plotted against the linear regression model for modern llama $\delta^{15}N$ values published by Samec, Yacobaccio, and Panarello (2018).

fall within the prediction interval (Table 2). In the case of Huirunpure, the mean $\delta^{15}N$ value falls outside the prediction interval, revealing that the nitrogen isotopic signal from this site is considerably higher (~ 2.1 ‰) than expected based on the correlation that llama bone collagen $\delta^{15}N$ values present with altitude in modern times (Samec, Yacobaccio, and Panarello 2018) (Figure 4). This pattern could be explained by the existence of more arid environmental conditions during the occupation of the layers 2 and 1 of Huirunpure (*ca.* 0–600 CE). This interpretation is based on the negative correlation between soil and plant $\delta^{15}N$ values and precipitation that has been widely documented in diverse parts of the globe (Amundson et al. 2003; Austin and Vitousek 1998). Moreover, a previous study carried out in the earlier archaeological site of Hornillos 2 – located in the same ravine as Huirunpure – found a significant difference when comparing the $\delta^{15}N$ values measured on wild camelids dated to the early and mid-Holocene, suggesting that the higher values identified during the mid-Holocene were caused by environmental changes that affected the nitrogen cycle on a regional scale (Samec, Morales, and Yacobaccio 2014). This interpretation is consistent with the information provided by the high-resolution paleoclimate records from the Andean highlands such as the Quelccaya ice core (Thompson et al. 2013) and the Huascarán ice cores (Thompson et al. 1995). In this sense, the chronology of Huirunpure's layers 1 and 2 coincides with the arid and/or warmer conditions identified in these records; the layer 2 of this site was dated to 2040 years BP (71 BCE–76 CE) whereas the layer 1 was dated to 1470 years BP (598–650 CE). In both cases, the mean $\delta^{18}O$ values measured during these time spans in the Huascarán and Quelccaya records – respectively – are well above the mean of the late Holocene series and remain quite similar to the mean $\delta^{18}O$ values measured during the Medieval Climate Anomaly (Thompson et al. 1995, 2013). At the same time, the peat core data from Cerro Tuzgle also suggests increased aridity for the 50 BCE-100 CE

period and high moisture variability after 550 CE (Schittek et al. 2016). Therefore, it is likely that the Huirunpure archaeological record analysed here represents occupations that occurred during periods of relative aridity, which might have affected the mean $\delta^{15}N$ values of the plant assemblages in the vicinity of the site without necessarily affecting the C_3-C_4 plants' proportions available for camelid consumption.

In summary, our results showed that the $\delta^{13}C$ and $\delta^{15}N$ values measured on the archaeological llama remains from Huirunpure and Chayal Cave do not necessarily fit the altitudinal pattern presented by modern data, although this should not be interpreted necessarily as the result of different herd management practices. In the case of Chayal Cave, the special characteristics of the ravine make the predominant isotopic signal of pastures immediately available to the herders stand apart from other plant communities located at similar altitudes in the Dry Puna. This particularity is sufficient to explain the slight deviation of the carbon stable isotope composition from the predicted values based on altitude alone. Also, environmental conditions and the time of the human occupation discussed here – approximately 1500 CE – could have reinforced this trend by promoting the development of C_3 plants within the area surrounding the site. Overall, the herding strategies employed by the occupants of the Cave seem to have had certain similarities with those practiced today, since both $\delta^{13}C$ and $\delta^{15}N$ values can be explained by the model based on the modern values, which is a product of a relatively narrow-range mobility strategy within those vegetal assemblages immediately controlled by each household (Samec, Yacobaccio, and Panarello 2018). In turn, humidity fluctuations at a regional scale could have affected the mean $\delta^{15}N$ values of the plants available for consumption near the site of Huirunpure, an aspect that might explain the difference between the $\delta^{15}N$ values from the llama remains recovered at the site and their modern counterparts. Another explanation for this pattern could be related to the existence of wider herding ranges during this time, which could have involved the use of pasturelands located downslope where plants' $\delta^{15}N$ values were higher, although this should also be reflected in higher $\delta^{13}C$ values due to the consumption of larger amounts of C_4 plants, which is not the case. At the same time, we cannot discard the existence of long-distance caravan trade networks that could have included interactions with adjacent regions affected by more arid conditions, where these llamas could have fed on similar proportions of C_3 and C_4 plants – than those available within the Dry Puna – but with higher mean $\delta^{15}N$ values due to aridity. To this point, the influence of warmer/drier environmental conditions on the $\delta^{15}N$ values measured on the bone collagen from the llama remains recovered at Huirunpure as opposed to the

existence of wider herding territories and/or the existence of extensive long-distance caravan circuits within the South-Central Andes during this period cannot be differentiated based on the data presented here and require further research.

In conclusion, and based on the evidence presented here, it is not implausible to conjecture that herd management strategies developed as early as 2000 years ago within the Dry Puna of Argentina, but stabilised and adopted a similar form that the one we observe today among traditional herders about 500 years ago.

Final Remarks

Overall, the preliminary results obtained by this research allowed us to gain a better understanding of the herding and landscape use strategies employed by the pastoralist groups that inhabited the Dry Puna during the 0–1500 CE time-span and their interaction with climate change. Carbon and nitrogen stable isotope compositions measured on bone collagen from llama remains recovered at the archaeological sites of Huirunpure and Chayal Cave were interpreted using the patterns identified in the $\delta^{13}C$ and $\delta^{15}N$ values measured on a modern llama data set. Our results showed the importance of considering the particular characteristics of the local vegetation as well as its possible modifications dictated by environmental change when evaluating llama herds' diet and mobility patterns within prehispanic pastoralist strategies. Nevertheless, the preliminary interpretations offered here still leave some issues unsolved and will undoubtedly benefit from future analyses of proxies such as $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values measured on prehispanic llama tissues, which will allow us to address aspects such as the participation of the archaeological sites analysed here within extensive circuits of long-distance llama caravan trade.

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