Living on the Edge: Climate-induced micronutrient famines in the ancient Atacama Desert?

Anne Marie E. SNODDY*[1][1], Charlotte L. KING*[1], Siân E. HALCROW[1], Andrew R. MILLARD[2], Hallie R. BUCKLEY[1], Vivien G. STANDEN[3], Bernardo T. ARRIAZA[4].

*Joint first authors

Corresponding author:
Annie Marie E. Snoddy (annie.sohler@otago.ac.nz)

Abstract

Investigations of the biological effects of climate change in past societies can increase our understanding of diverse human adaptations to environmental instability. Individuals from ecologically marginal regions are particularly susceptible to climate-induced resource stress. In this study, we create and test an integrated paleoenvironmental and bioarchaeological model of the biosocial effects of environmental change on nutritionally based health outcomes. We present new evidence for scurvy (severe vitamin C deficiency) in ancient human remains (N = 187) from the hyper-arid northern Atacama Desert, South America, which we interpret as indicating episodes of low dietary diversity. Skeletal evidence for scurvy was found to increase significantly across the Archaic-Formative transition (c. 3500–1500 BP). Previous paleoenvironmental and isotopic research indicates that this transition is also marked by increased frequency of ENSO events, and a dietary shift to horticulturalism rather than marine-focused hunting and gathering. Here we build on this modeled environmental and subsistence change, and propose that increased ENSO events may have contributed to social adaptations to resource insufficiency, cyclicity of marine resource use, and ultimately an environment favorable to periodic micronutrient famines and the osteological manifestations of scurvy.

[1] Department of Anatomy, University of Otago, 270 Great King Street, Otago, New Zealand 9016.

[2] Department of Archaeology, Durham University, South Rd, Durham DH1 3LE, United Kingdom.

[3] Departmento de Antropología, Universidad de Tarapacá, Arica, Arica y Parinacota, Chile.

[4] Instituto de Alta Investigación, Universidad de Tarapacá, Antofagasta 1520, Arica, Chile.

Introduction

The Atacama Desert has hosted human populations for at least eleven millennia, despite its status as the driest hot desert in the world, its propensity for extreme weather disturbances, and the relative paucity of both freshwater and terrestrial food resources (Arriaza et al., 2001; Marquet et al., 2012; Sandweiss, 2004). Human populations living in arid environments are particularly vulnerable to climatic changes. In these ecologically marginal regions, slight shifts in temperature or precipitation can have cascading effects on biodiversity, species abundance, and resource availability and, by extension, resource stress and health outcomes in human populations (Lioubimtseva & Henebry, 2009; Walther et al., 2002; Zhang et al., 2007). In hyper-arid environments in particular, many species are already functioning close to their limits and are therefore susceptible to population extinction in the face of atypical climatic events (Whitford &Wade, 2002). The Atacama region is also significantly affected by variation in weather patterns, in particular El Niño Southern Oscillation (ENSO) cycles, which periodically disrupt fisheries and flood agricultural land (Houston, 2006a; Montecino & Lange, 2009; Sepúlveda et al., 2014).

Changing environmental conditions in the past have been proposed as a major driver of cultural change in the Atacama region (de Bryson et al., 2001; Marquet et al., 2012). Most famously, increased marine and desert productivity in the Archaic period have been linked with population growth, an increase in accumulation of natural mummies, and the advent of artificial mummification practices (Marquet et al., 2012). Similarly, increased highland aridity associated with extreme ENSO cycles has been suggested as a driver of agriculturalist migration into coastal valleys, heralding the advent of agriculture in the Formative Period (Marquet et al., 2012; Rothammer et al., 2009).

In periods of climatic flux, human populations in arid marginal environs are particularly subject to dietary stress, reduced dietary diversity, caloric insufficiency,

micronutrient (vitamin and trace mineral) deficiencies, and associated negative health effects (Tulchinsky, 2010; Wheeler & von Braun, 2013). Research on biosocial adaptations to climate change in ancient populations, particularly those living in resource poor or marginal regions, can help us understand how human populations in the past responded to resource stress. Modern human groups living in agriculturally marginal areas are often characterized by dietary variability, with flexibility in subsistence strategy central to their social resilience (Turner et al., 2003). When contemporary populations experience resource stress, they may decide to change or supplement staple foods to stave off malnutrition (e.g. Lockett et al., 2009), but literature on the use of these so-called "famine foods" in the context of climate change are few (see Grivetti & Ogle, 2000). Research in these areas can shed light on how historical and socio-cultural conditions shape or constrain those subsistence strategies, and their relative success over the short- and long-term (Robbins Schug, 2011; Berger & Wang, 2017).

Here we focus on the Northern Atacama Desert in an attempt to model how environmental change may affect human health and diet in archaeologically visible ways. In this region, the Archaic-Formative Period transition (c. 3,500–1,500 BP) coincides with an increase in both ENSO frequency and intensity (Gayo et al., 2012; Latorre et al., 2003; Magilligan et al., 2008; Santoro et al., 2017). This transition is characterized by human population movement from coastal river deltas to inland valley sites (Arriaza et al., 2008), and a shift from marine hunting and gathering to a mixed subsistence economy incorporating Andean and Meso-American cultivars (Andrade et al., 2015; King et al., 2018a; Pestle et al., 2015). We examine the biosocial impact of these environmental conditions and subsistence changes in human populations in the Atacama Desert, focusing on how climatic perturbations affected dietary diversity and the prevalence of micronutrient deficiencies.

In this chapter, we provide a multifaceted model of biosocial change during the transition to agriculture in the northern Atacama Desert, incorporating paleoenvironmental, isotopic and paleopathological evidence. In particular we propose a relationship between El Niño events, subsistence choices, and micronutrient deficiencies. We test our model by combining previously published isotopic results from the northern Atacama with new skeletal evidence of vitamin C deficiency from the Arica region. We examine whether shifts between terrestrial and marine resource-use might result in correlations between human isotope values and vitamin C status by comparing the isotopic signatures and vitamin C content of foods known to be exploited or cultivated in the ancient Atacama. Finally, we suggest how future researchers might continue to develop this model by incorporating additional skeletal markers of stress and disease and greater chronological resolution of archaeological material from this region.

Archaeological context: The Atacama Desert and the transition to agriculture

The Atacama Desert in Northern Chile and Southern Peru is the driest inhabited environment on earth and probably the oldest extant desert (Clarke, 2006). The moisture-blocking effect of the Andes to the east and the drying action of anticyclonic air masses from the Pacific High-Pressure Belt mean that rainfall averages less than 2mm per year with some areas going for decades without precipitation (Houston, 2006b,c; Rundel et al., 2007). River valleys fed by the seasonal Andean rains create oases along the western coast and islands of fog provide scattered patches of higher than normal biodiversity in the coastal hills (*Cordillera de la Costa*) (Cereceda et al., 2008 a; b). However, terrestrial species abundance remains low even within these isolated sanctuaries and terrestrial organisms are largely limited to a few vascular plants, insects, and small vertebrates such as lizards and rodents (Hesse, 1984; Langstroth, 2011; Rundel et al., 2007). Before the introduction of Andean and

Mesoamerican domesticates in the Formative Period there were few plant species available to be exploited. Estuarine plant species are an important exception to this and were likely a significant part of the Archaic diet (as per Holden, 1994; Reinhard et al., 2011).

In contrast with terrestrial conditions, the upwelling of the Humboldt Current off the western coast of the Atacama Desert creates one of the most resource-rich marine environments in the world. Here, oxygen-rich cold water fosters the presence of a large mass of phytoplankton and kelp (Montecino & Lange, 2009). These organisms are the trophic foundation for a vast number of consumer species, including a wealth of marine mammals, seabirds, bony and cartilaginous fish, and mollusks (Miloslavich et al., 2011:10-11; Montecino & Lange, 2009:67; Tam et al., 2008). This rich marine environment was key in enabling early human occupation of the coastal desert in the past and is still the economic foundation of many communities there today (Arriaza et al., 2008; Peña-Torres & Basch, 2000; Reinhard et al., 2011).

The El Niño/Southern Oscillation phenomenon has significant environmental effects in the coastal Atacama Desert. ENSO describes linked, cyclic changes in ocean temperature and atmospheric currents in the Pacific, which currently occur every two to five years (Guilyardi, 2005). These changes are quantified by measuring the variation in atmospheric pressure and ocean temperature between North Western Australia and Tahiti (Southern Oscillation Index, or SOI) (Kovats et al., 2003). Negative SOI values are indicative of an El Niño event, which is associated with oceanic warming, resulting in drought in the Western Pacific and heavier than normal rainfall in the Eastern Pacific (Dilley & Heyman, 1995; Jaksic, 2001). Conversely, positive SOI values are associated with a La Niña oceanic cooling event, which results in abnormally heavy precipitation in Australasia and drought in Western South America (Kiladis & Diaz, 1989). During El Niño cycles the warming of the eastern Pacific Ocean causes a decrease in marine biodiversity along the South American coast

associated with large-scale die-offs of microorganisms, mollusks, and vertebrates. Fish species diversity changes, with cold water fish disappearing and warm water fish moving down the South American coast to inhabit waters which were previously too cold for them (Sandweiss et al., 2004; Tam et al., 2008; Taylor et al., 2008). In general, these cyclic changes have short-term and low-level effects on resources available and growing seasons; however, extreme El Niño events occur on a decadal scale and are associated with marine species die-offs and changes, as well as significant resource scarcities (Glantz, 2001).

Despite the dearth of terrestrial resources in the Atacama Desert, it has been continuously occupied by humans since c. 11,000–10,000 BP, with the rich marine environment allowing maritime hunter-gatherers to become sedentary remarkably early in prehistory. By 8,000 BP a culture known as the Chinchorro had developed in the coastal northern Atacama. This Archaic Period group relied heavily on marine subsistence and developed a complex system of mummification of the dead (Arriaza et al., 2008; Marquet et al., 2012; Standen et al., 2018). A marine hunter-gatherer complex persisted in the northern Atacama for several thousand years, with occupation centered almost exclusively on the coastal deltas of the few and far-between rivers in the area (Arriaza et al., 2008; Santoro et al., 2005). After around 3,500 BP, however, a shift in human occupation pattern is archaeologically observable. Although some coastal sites remained in use (e.g. Tiliviche, Playa Miller), the settlement became centered in the interior river valleys and horticulturalism commenced (Muñoz & Gordillo, 2016; Núñez, 1986; Núñez & Santoro, 2011). The advent of agriculture in the region marked the beginning of the Formative Period (c. 3,500–1,500 BP), where diet shifts to incorporate Andean cultivars such as quinoa, beans, and squashes, as well as maize and (probably) domesticated camelids, alongside the marine foods which characterized the preceding Archaic Period (King et al., 2018a; Pestle et al., 2015; Santana-Sagredo et al., 2015).

Multiple lines of paleoenvironmental evidence suggest that the adoption of agriculture during the Archaic-Formative Period transition is correlated with changes to ENSO frequency and intensity (de Bryson et al., 2001; Muñoz & Chacama, 2012). Analyses of changes in the dominant species within shell middens and marine faunal remains from archaeological sites in coastal Peru suggests that before 5,800 BP, ENSO events either did not occur or were less significant than they are today. After 3,200–2,800 BP, however, they increased in both frequency and severity (Sandweiss et al., 2004; 2001). Analysis of watershed stratigraphy in coastal Southern Peru and plant microfossil/faunal remains from the central Chilean Atacama also suggest that large ENSO-related floods did not occur before the Mid-Holocene and discrete elevations in the water table occurred around the Archaic-Formative transition (Gayo et al., 2012; Latorre et al., 2003; Magilligan et al., 2008). Previously published paleoclimatic data are summarized in Figure 1.
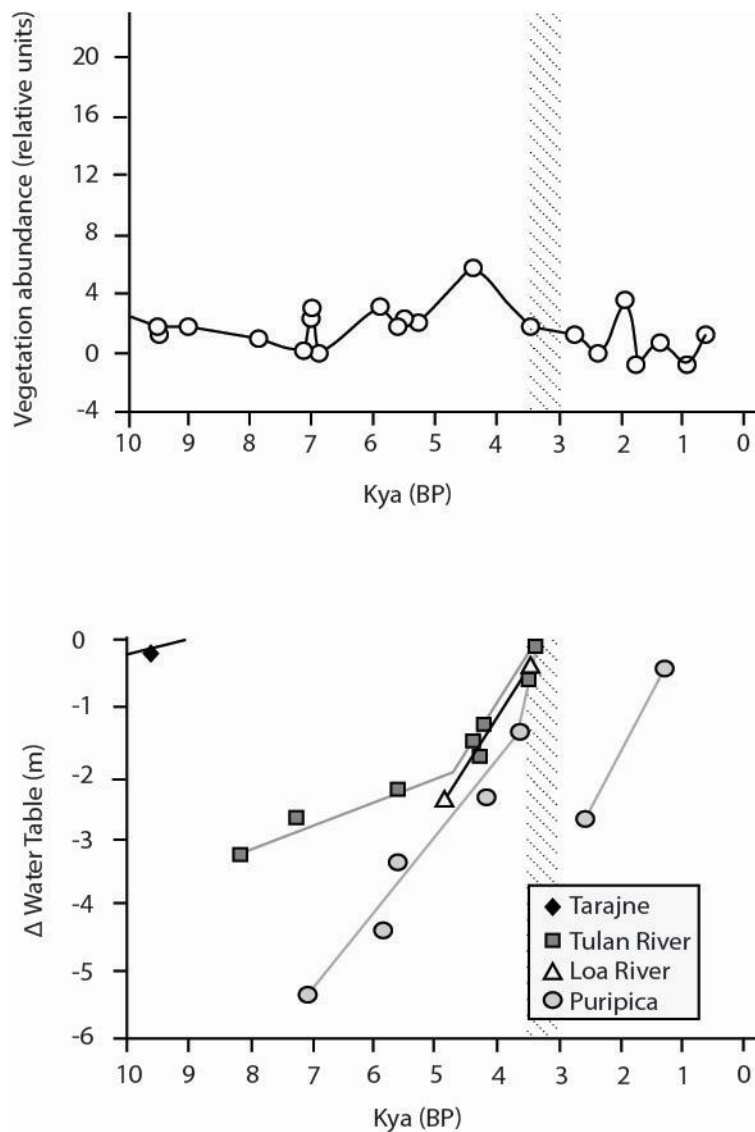
Figure 1

Biosocial effects of increasing ENSO frequency and intensity

The volume of bioarchaeological data from pre-Columbian populations of the northern Atacama is ever-increasing, such that it is now possible to begin to develop regional models of how changes to ENSO cycles may have led to both biological and social responses in the human populations here. Previous investigations into the biosocial effects of shifting human-environmental dynamics have focused on the dietary changes necessitated by changing ENSO conditions. For example, isotopic evidence suggests that a slow but significant shift to a more terrestrial diet occurs at the Archaic-Formative transition (e.g.

Díaz-Zorita Bonilla et al., 2016; King et al., 2018a; Santana-Sagredo et al., 2015), and this may be linked to changing viability of terrestrial agriculture and depression of the fisheries during extreme El Niño events (Moreno et al., 2009; Sandweiss et al., 2001; Williams et al., 2008). In addition to broad-scale change in dietary scope, almost all isotopic studies in the region have noted a shift towards mixed subsistence strategies after the Archaic-Formative transition (e.g., King et al., 2018a; Mora et al., 2017; Pestle et al., 2015). It is possible that dietary variability may be linked to periodicity of ENSO cycles (King et al., 2018a; Mora et al., 2017), although a lack of tight chronological control over site occupation periods has made this difficult to test previously (King et al., 2018a; Moreno et al., 2009).

Extreme ENSO events, though few and far between, may also be associated with dietary restriction. The increasing periodicity and intensity of ENSO cycles during the Formative Period (de Bryson et al., 2001; Muñoz & Chacama, 2012) could, conceivably, be linked to increased frequency of short-term famine events, with strong ENSO cycles periodically depleting either terrestrial or marine resources making it difficult to maintain caloric intake. New incremental isotopic techniques have potential for assessing dietary changes and physiological stress responses in the Atacama and how seasonal availability of resources may correspond to periods of stress relating to food scarcity (e.g. King et al., 2018b; Knudson et al., 2015; Mora et al., 2017). More broadly, incremental isotopic analysis is an important developing area of bioarchaeological research that may shed light on whether stress episodes are occurring during periods of climatic change (Fuller et al., 2005; Reitsema, 2013).

ENSO-driven changes to diet may also result in micronutrient deficiencies, as communities increasingly rely on vitamin-poor foods in times of resource stress (WHO, 1999). There is very little published data on changes to nutritional status across the Archaic-Formative transition (Snoddy et al., 2017). One problem with research on this question is that

the majority of nutritional deficiencies experienced by contemporary human groups undergoing resource stress (e.g. protein-energy malnutrition, most vitamin or mineral deficiencies) will not create diagnostic skeletal lesions (Huss-Ashmore & Goodman, 1982; Ortner, 2003). On the other hand, vitamin C deficiency, a condition associated with general micronutrient malnutrition, is one of the notable exceptions to this problem (see below). There is significant variation in the vitamin C content of different naturally occurring and cultivated resources in the Atacama Desert; for example, many marine mammal organs and kelp have high levels of bio-available vitamin C, while maize has negligible amounts of this nutrient (USDA, 2019). It is, therefore, possible that changes to isotopic values in human tissues that indicate an increase in different food resources may correlate with shifting micronutrient availability and that this may be archaeologically visible as skeletal lesions of scurvy within an assemblage.

Scurvy and dietary diversity in the past

Although general nutritional status cannot be directly inferred from skeletal remains, certain micro-nutritional deficiencies may leave diagnostic skeletal lesions and can be a useful proxy for overall dietary quality. Scurvy, a disease of prolonged vitamin C deficiency, is of particular interest in the exploration of environmental change and subsistence strategy in the past, as it is directly related to dietary diversity and quality (Buckley et al., 2014; Snoddy et al., 2017; 2018). Vitamin C (ascorbic acid) is a nutrient necessary for enzymatic functions essential for life, including the synthesis of collagen (Levine & Padayatty, 2014). In the absence of vitamin C, widespread signs related to defective collagen synthesis, including minor hemorrhage into the subperiosteal space of bones, will occur (Brickley & Ives, 2008; Snoddy et al., 2018). This hemorrhage is associated with increased, localized cortical bone surface porosity and—following the reintroduction of at least some dietary vitamin C—the

formation of islands of subperiosteal new bone. These osseous lesions mean that scurvy may be identified in human skeletal remains, particularly in infants and young children who are undergoing rapid growth (Brickley & Ives, 2008; Snoddy et al., 2018), allowing periods of resource scarcity and poor dietary quality in the past to be recognized (e.g. Buckley et al., 2014; Geber & Murphy, 2012; Snoddy et al., 2017).

Most vertebrate animals are capable of synthesizing vitamin C themselves but humans and other primates must meet their requirement through dietary sources such as fruits, vegetables, and the organs—particularly the livers—of animals who produce it endogenously (Levine & Padayatty, 2014). Cereal crops and meat (muscle tissue) are very poor sources of vitamin C and populations that rely exclusively on these as staple foods due to resource scarcity or underutilization are at risk for developing scurvy as well as other micronutrient deficiencies (Cheung et al., 2003; WHO,1999). The identification of scurvy within a skeletal assemblage can, therefore, be considered a reasonable proxy for poor dietary diversity in the past (Snoddy et al., 2017). Although other lines of evidence are necessary for interpretation, the presence of scurvy in multiple individuals within an assemblage should be considered in terms of implications for subsistence strategy (Snoddy et al., 2017), environmental instability (Buckley et al., 2014; Robbins Schug & Blevins, 2016), and resource allocation practices (Crandall, 2014).

Generally, studies of scurvy in the past have found low prevalence rates, well below 20% of studied individuals. However, this prevalence rate may increase when populations are put under extreme resource stress, for example in Geber and Murphy's (2012) study of a 19th-century Irish famine population. Previous research on vitamin C deficiency in western South America has been limited to case studies or case-series centered on agricultural coastal Peru (Klaus, 2014; 2017; Ortner et al., 1999). Several of the authors of this chapter published a small case-series of an adult and four perinates with possible scurvy from the early

Formative Period site of Quiani-7 (ca 3,600-3,400 BP) in the Northern Chilean Atacama (Snoddy et al., 2017). The high prevalence (41.6%; 5/12) of potential cases here is intriguing, particularly given the correlation between the use of this site and the proposed onset of more intense and frequent ENSO events in the early Formative Period. However, the small sample size and lack of an Archaic Period comparative population precluded broader characterisation of the potential effects of subsistence transition on vitamin C status, and by extension, resource use and availability in this region. This chapter provides evidence from larger Archaic and Formative Period cohorts needed to more completely explore the potential relationship between micronutrient malnutrition and paleoenvironment in the Northern Atacama Desert.

Bringing the lines of evidence together: An integrated model of ENSO driven health outcomes in the Atacama Desert

Changes to both resource and micronutrient availability in the Atacama region are expected to correlate with poor health outcomes, some of which would be bioarchaeologically visible in cemetery populations (figure 2). For example, we expect periods of increased ENSO intensity to result in cyclical resource use as terrestrial and marine ecosystems are alternately affected by El Niño and La Niña events. This resource depletion likely would result in social and biocultural responses to ensure population survival. For example, contemporary hunter-gatherer and horticultural populations adapt to environmental instability by increasing adaptive diversity or shifting the predominant cultivated or exploited foods. Flexibility in food choices is an adaptive social response to vulnerability (Turner et al., 2003). However, even with social buffering, populations may still pay a biological cost (do Nascimento et al., 2012; Muller & Almedom, 2008; Seo & Mendelsohn, 2008). In the ecologically vulnerable Northern Atacama, cyclical changes in resource use may be linked to

periodic 'micronutrient famines' as populations decrease dietary variety in favor of fewer, calorie-rich but micronutrient-poor crop-based foods. We predict that these dual processes will result in increased paleopathological evidence for micronutrient deficiencies and periodic recovery, isotopic heterogeneity, and potential nutritional stress signals in sequential isotopic results.

We also anticipate changes to demography to occur in this model. In particular, we expect infant mortality rates to rise with resource stress. As the most biologically vulnerable members of society, infants and young children generally bear the brunt of environmental pressures (Caldwell, 1996; Halcrow & Tayles, 2008; Kane, 1987; Lewis, 2018; Snoddy et al., 2017). Demographic changes across the Archaic-Formative transition have not been studied in depth in the Northern Atacama (see Moreno et al., 1992 for an exception), but merit attention in the future as a potential measure of population health and fertility change.
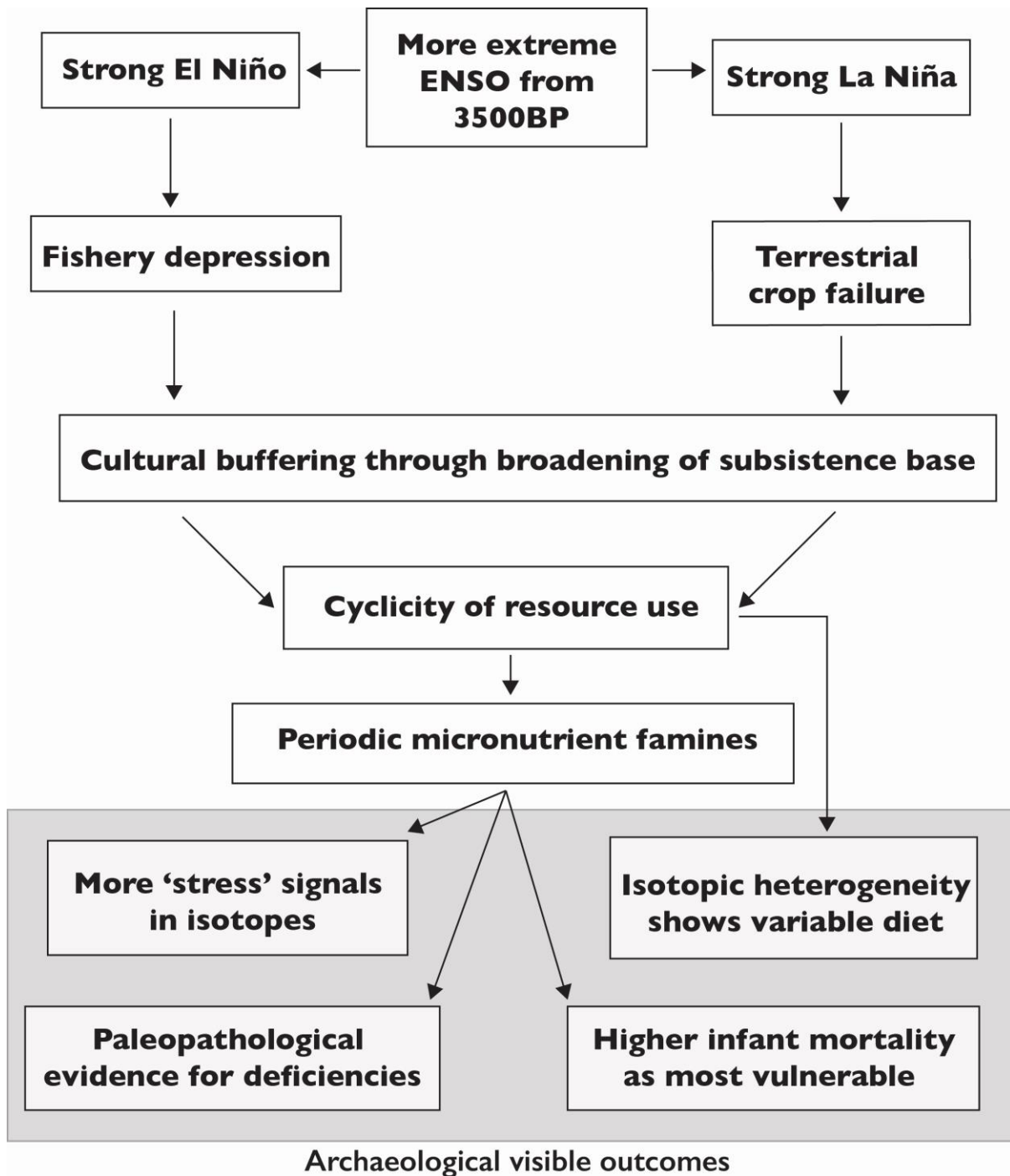
Figure 2

There is a potential slew of other social and environmental factors affecting the nature

of the Archaic-Formative transition in the northern Atacama. For example, ENSO effects in

the highlands have been proposed as a driver of migration to the study area during the

Formative Period, resulting in social interaction between groups and the increased importance

of Andean domesticates (Rothammer et al., 2009). Ultimately this population movement may have led to the advent of new cultural norms in the area, such as the practice of building burial tumuli using domesticated crop vegetal layers (Focacci & Erices, 1973), likely reflecting the increasing cultural significance of these food sources. Here we focus on observable paleopathological outcomes of subsistence choices for simplicity's sake, but recognize that as the model is tested more nuanced social factors will need to be incorporated.

Human remains from the Atacama region and their archaeological context

Our archaeological sample includes skeletal elements, defleshed mummies, and minimally mummified (<⅓ of bones obscured by soft tissue) individuals, who are curated at the Museo San Miguel de Azapa, Arica. This chapter reports on the results of paleopathological analysis conducted on a total of 187 individuals, 72 from the pre-transition Archaic Period coastal sites of Morro-1 and Morro 1-6, and 115 from the early agricultural Formative Period valley sites of Azapa (AZ) 14, 70, 71, 75, 75d, 75e, and 115. All individuals were from sites in the city of Arica (18°S 20°W) and adjacent Azapa Valley.

Morro 1 and Morro 1-6 are located on the massive coastal bluff of El Morro (18°30S, 70°70W) on the southern margins of the modern port-city of Arica. Morro 1 is situated on the top of El Morro overlooking the Pacific, while the smaller burial ground of Morro 1-6 is found approximately halfway up its north-eastern slope. Both sites likely represent different periods of use of a single, large cemetery rather than two discrete cemeteries (Sutter & Mertz, 2004; Standen, 2003). Material cultural evidence in the form of grave-goods (e.g. specialized maritime occupational equipment and plant-based textiles) and the presence of artificially mummified individuals indicates an ideological association between these interments and the Chinchorro Cultural Complex (Allison, 1984; Focacci & Chacón, 1989). Paleofaunal and paleobotanical remains from Morro 1 show evidence for exploitation of mollusks

(*Concholepas* and *Choromitylus spp*), sardines (*Sardinopsis spp*), pelican (*Pelicanus spp*), marine mammals such as pinnipeds (*Phoca hispida* and *Otaria flavescens*) and cetaceans, woody shrubs such as taramungo (*Propsis spp*), wild reeds and grasses (Standen, 2003). Human coprolites from Morro 1-6 provide direct evidence for the consumption of sedges (*Cyperacaea spp*), wild tomato (*Solanaceae spp*), and aquatic grasses (*Scirpus spp*). (Reinhard et al., 2011). Morro 1 appears to have been in continual use for two thousand years, with desiccated human muscle from this site radiocarbon dating to 5210–3720 BP, while Morro 1-6 appears to have been used for a period of ~400 years (4360–3945 BP) (Allison, 1984; Focacci & Chacón, 1989; Standen et al., 1997; Standen & Sanhueza, 1984).

The Azapa Valley sites are clustered along the banks of the San Jose River, ~8–15 km from El Morro and the Port of Arica (18°–19°S 70°–71°W). All analyzed individuals are associated with the Early Formative Period (*ca*. 3,500-2,500 BP) Azapa or Late Formative Period (*ca*. 2,500-1,500 BP) Alto Ramírez cultures. Paleobotanical and paleofaunal remains from all sites and cultural phases indicate a mixed maritime-horticulture economy with cultivars such as lima beans (*Phaseolus lutanus*), chilies (*Capcisum spp*), cassava (*Manihot esculenta*), maize (*Zea mays*), sweet potato (*Ipomea bata*), quinoa (*Chenopodium quinoa*), and achira (*Canna edulis*) variably present along with marine resources such as mollusks (*Choromythilus, Choncholepas,* and *Fisurellas spp*), mackerel (*Trachurus spp*), and camelids (Muñoz, 1980; 1987; Santoro, 1980a; b; 1982). Uncalibrated radiocarbon dates are available for all sites. A summary of the paleofaunal, paleobotanical, and material culture evidence of the subsistence economy, chronology, and sample size for each site is provided in Table 1.

Table 1

Site and culture	Botanical/ archaeozoological remains	Subsistence-related material culture	Economy	Site dates (dating method)	Chronological phase of analysed individuals	Number of individuals analaysed
Morro 1, Chinchorro (Standen, 2003; Reinhard et al., 2011)	Molluscs, crustaceans, seaweed, fish, marine mammals and birds; Abundant camelid skins and fibre but few bones; Wild plant fibres and seeds present in coprolites	Hunting, fishing and marine gathering instruments (harpoons, fishhooks, nets, ropes, 'chopes'); terrestrial hunting instruments (spear, darts, projectile points)	Marine hunter-gatherer	5,450-3,700 BP (uncal. radiocarbon: Arriaza et al., 2005; Standen, 1997)	Late Archaic	70
Morro 1-6, Chinchorro (Focacci and Chacón 1989)	Molluscs, crustaceans, seaweed, fish, marine mammals and birds; Abundant camelid skins; Plant fiber present in coprolites	Hunting, fishing and marine gathering instruments (harpoons, fishhooks, nets, ropes, 'chopes'); terrestrial hunting instruments (spear, darts, projectile points)	Marine hunter-gatherer	4,310-3,500 BP (uncal. radiocarbon: Focacci and Chacón, 1989; Standen et al., 2018)	Late Archaic	2
Az14, Alto Ramirez (Santoro, 1980a)	Maize (*Zea mays*), quinoa (*Chenopudium quinoa*), manioc (*Manihot* sp.), camote (*Ypomea batata*), achira (*Canna edulis*), pallares (*Phaseolus lunatus*), chillies (*Capsicum spp*), gourd (*Cucurbitaceae*); shellfish and fish	Agricultural tools (shovel handles, digging sticks); Marine hunting and fishing instruments ('chopes', harpoons, fishhooks); Terrestrial hunting instruments (bow, wooden points)	Broad-spectrum agriculturalists	2,900-2,410 BC (uncal. radiocarbon: Santoro,1980a; Rivera, 1987)	Early Formative	7

Az70, Alto Ramirez (Focacci and Erices, 1972 and 1973; Romero et al., 2004)	Maize (*Zea mays*), Achira *(Canna edulis), manioc (Manihot esculenta)*, pallar *(Phaseolus lunatus)*, quinua silvestre (*Amaranthaceae*), beans *(Phaseolus vulgaris)*, Cucurbitaceae (*Lagenaria spp*?)	Agricultural tools (wooden digging/tilling, sticks); Hunting instruments (darts, spear tips)	Broad-spectrum agriculturalists	2,490-1,930 BP (uncal. radiocarbon: Rivera, 1996; Romero et al., 2004)	Early Formative	4
AZ 71, Azapa and Alto Ramirez (Santoro, 1980a, b)	Maize (*Zea mays*), chillies (*Capsicum*), quinoa (*Chenopodium quinoa*), achira (*Canna edulis*), lima beans (*Phaseolus lunatus*), and molluscs	Marine hunter-gatherer artefacts (fishhooks, harpoons, lithic points, sharktooth knives, fishing lines); Terrestrial hunting (leathers and skins of terrestrial animals, wooden points)	Broad-spectrum agriculturalists	2,855-2,560 BP (uncal. radiocarbon: Santoro, 1980b)	Early/Late Formative	18
Az115, Alto Ramirez (Muñoz, 2017)	Maize (*Zea mays*), Cucurbitaceae (*Lagenaria spp?*), sweet potato (*Ypomea batata*), manioc (*Manihot esculenta*); Camelids, dog (*Canis familiaris*), cuys (*Cavia porcellus*)	Miniature hunting instruments (darts and bows, vegetal thorns)	Broad-spectrum agriculturalists	1,900-1,300 BP (uncal. radiocarbon: Muñoz, 2017)	Late Formative	23
Az75, Az75D, and Az75E; Alto Ramirez (Focacci, 1983; Aufderheide et al. 2003)	Achira *(Canna edulis)*, Cucurbitaceae (*Lagenaria spp*?), mesquite (*Prosopis spp*); Camelid bones, molluscs	Agricultural tools (shovel handle, digging sticks); Terrestrial hunting instruments (bow, wooden points, darts)	Broad-spectrum agriculturalists	2,350-1,500 BP (uncal. radiocarbon: Aufderheide et al., 2003; dates from AZ 75 only)	Late Formative	63

Combining isotopic data and paleopathological analysis of human remains

The primary skeletal data in this sample are interpreted with reference to previously published isotopic data (from Andrade et al., 2015; Andrade & Castro, 2016; Aufderheide et al., 2002, 1994, 1993; King et al., 2018a; Pestle et al. 2015; Pietruzelli et al. 2012; Poulson et al., 2013; Roberts et al., 2013; Santana-Sagredo et al. 2015; Tieszen et al., 1995; Torres-Rouff et al., 2012). Dietary differences between the Archaic and Formative Period sites have previously been pointed out by multiple studies (King et al., 2018a; Santana-Sagredo et al., 2015; Torres-Rouff et al., 2012). In this study, previous results were synthesized and dietary change was assessed using Wilcoxon tests (as a proxy for an overall dietary change), and Levene's tests for homogeneity of variance (as a proxy for differences in dietary variability). All statistical tests were conducted using R (R core team, 2013).

Adult age was estimated using methods summarized in Buikstra and Ubelaker (1994) with degenerative changes to the pubic symphysis and auricular surface (Brooks & Suchey, 1990; Meindl & Lovejoy, 1989) preferentially employed for adult age estimation, according to skeletal completeness. Adult age was broadly categorized as young (20–34 years), middle (35–49 years), and old (50+ years) adults to account for the large margin of error associated with current age estimation methods. In cases where methods yielded an estimate intermediate between two age categories the individual was assigned to a broader age group (e.g. 20–49 years). Adult sex was assessed from sexually dimorphic cranial and pelvic features (Acsádi & Nemeskéri, 1970; Phenice, 1969) and individual sex was categorized as "probable male/female", "possible male/female", and ambiguous (unknown) sex, after Buikstra and Ubelaker (1994). Infant and child age was estimated via dental development (Ubelaker, 1989), epiphyseal fusion (Buikstra & Ubelaker, 1994; Scheuer & Black, 2000), and diaphyseal length (Fazekas & Kósa, 1978; Maresh, 1970). Dental development was employed for age estimation where possible as this is the preferred method for estimating age

from juvenile skeletal remains (Lewis, 2007: 38). For paleoepidemiological analysis, individuals younger than 15 years old at death were considered "non-adults" and individuals between one and 20 years old at death were grouped into five-year age categories. Individuals aged between the third-trimester fetal period and one year were grouped into a 0–0.9 year age category.

Macroscopic skeletal abnormalities were recorded after Ortner (2003:49). Analog radiographs in anteroposterior and lateral views were obtained of any elements that exhibited macroscopic abnormalities. However, differential diagnosis of scurvy was undertaken using macroscopic lesions after Snoddy et al. (2018) with individuals categorized as "probable scurvy", "possible scurvy", or "no evidence of scurvy" according to the number and diagnostic strength of features exhibited[5]. The total number of probable, possible, and combined probable/possible cases of scurvy in each temporal cohort was compared via Pearson's chi-squared test. We used published data (Fediuk et al., 2002; Geraci & Smith, 1979) or USDA Food Composition Database (USDA, 2019) to assess the vitamin C content of exploited or cultivated organisms in the Archaic and Formative Period, and identify potential sources of deficiencies.

Paleopathological analysis and isotopic patterns across the Archaic-Formative transition

The Archaic Period cohort was composed of 55 adults and 17 infants and children (<15 years). Categorical age estimation was possible for 43 adults and all infants and children. Sex estimation was possible for 83.3% (45/54) individuals over 18 years and two skeletonized non-adult mummies whose genitalia had previously been recorded before

---

[5] For the full diagnostic scheme and detailed background information on the skeletal lesions of scurvy see Snoddy et al., 2018.

defleshing. The sex distribution of the Archaic Period cohort was nearly 1:1 (1.04:1), slightly favoring females when probable and possible sex assessments were grouped. Analysis of the Formative Period cohort revealed an age-at-death composition of 58 adults and 57 infants and children. Age estimation was possible for 104 individuals, including all infants and children. Sex estimation was possible for 82.5% (52/63) of individuals over 18 and one skeletonized non-adult mummy. The sex distribution was 1.4:1 favoring females when probable and possible sex assessments were grouped.

In this sample, the majority of diagnostic and suggestive lesions for scurvy consisted of subperiosteal new bone or clustered, fine porosity at vascular and entheseal sites in the skull (see Snoddy et al., 2018: Table 2 therein), particularly the interior mandible, posterior maxilla, and maxillary palate. The prevalence of combined "probable" and "possible" scurvy cases was extraordinarily high across both cohorts for an archaeological sample with at least 20% of individuals affected in both periods (Archaic Period: 20.8%, 15/72; Formative Period: 34.8%, 40/115). However, the number of affected individuals was significantly higher in the Formative Period cohort ($X^2 = 4.150$, p = 0.042).

The demographic composition of affected individuals also differed between the cohorts with adults (>15 years) and infants and children approximately equally affected in the Archaic Period group (1:1.1), while more infants and children were affected in the Formative Period group (4.7:1). However, this difference was not statistically significant for probable, possible, or combined probable/possible cases. The frequency and prevalence of probable and possible disease cases in each demographic group in the Archaic and Formative Period cohorts are provided in Table 2. Of interest, the majority of scorbutic lesions recorded consisted of subperiosteal new bone, indicating that vitamin C had been at least partially restored before death (Brickley & Ives, 2008). This suggests that these individuals suffered from episodic, possibly cyclical, extreme micronutrient malnutrition.

Table 2

Archaic Period				
Age-at-death	Prob. Scurvy (f)	Prevalence (%)	Poss. Scurvy (f)	Prevalence (%)
0-0.9	1/4	25%	0/4	-
1-4.9	6/7	85.7%	0/7	-
5-9.9	0/4	-	0/4	-
10-14.9	0/2	-	0/2	-
15-19.9	0/1	-	0/1	-
20-34	0/20	-	2/20	10%
20-49	0/3	-	0/3	-
35-49	0/12	-	0/12	-
35-50+	1/3	33.3%	0/3	-
50+	0/4	-	0/4	-
Unknown Age (adult)	1/12	8.3%	4/12	33%
Male	1/23	4.3%	3/23	13%
Female	2/24	8.3%	0/24	-
Unknown Sex: Subadults	6/15	40%	0/15	-
Unknown Sex: Adults	0/10	-	3/10	30%

Formative Period				
Age-at-death	Prob. Scurvy (f)	Prevalence (%)	Poss. Scurvy (f)	Prevalence (%)
0-0.9	8/17	47%	1/17	5.8%
1-4.9	14/27	51.8%	2/27	7.4%
5-9.9	7/12	58.3%	0/12	0%
10-14.9	0/1	-	1/1	100%
15-19.9	1/7	14.2%	0/7	-
20-34	2/16	12.5%	2/16	12.5%
20-49	0/1	-	0/1	-
35-49	0/20	-	1/20	5%
35-50+	1/2	50%	0/2	-
50+	0/1	-	0/1	-
Unknown Age (adult)	0/11	-	0/11	-
Male	2/22	9%	0/22	-
Female	2/31	6.4%	3/31	9.6%
Unknown Sex: Subadults	29/56	51.7%	4/56	7.1%
Unknown Sex: Adults	0/6	-	0/6	-

As previous isotopic studies in the region have indicated (Andrade et al., 2015; King et al., 2018a), there are clear changes to diet across the Archaic-Formative transition. Isotopic

values are significantly different between the two phases (W=1590, p<0.001), and there is a greater range of values in the Formative, though the variance is not significantly different (F=0.45674, df = 15, p=0.08). We compared baseline δ^{15}N values from resources of the northern Atacama Desert with the vitamin C content of species exploited or cultivated in the Arica region. These data show that primary grains used in the region (quinoa and maize) have both low vitamin C content and low δ^{15}N values. The primary terrestrial crops that could provide sufficient vitamin C include Andean domesticates such as squash, tomatoes and capsicum species. The organs of high trophic level marine resources (high δ^{15}N values) such as seals and sealions have the potential to meet all vitamin C needs for the populations, but only if people were exploiting internal organs and skin as well as the muscle tissue.

Discussion

We proposed a framework in which dietary change and micronutrient deficiencies were fundamentally related to increased ENSO frequency and intensity during the Formative Period in the Northern Atacama region. In this study, isotopic evidence collated from multiple areas of the Northern Atacama in northern Chile indicates that the Formative Period was characterized by dietary variability, as indicated by a large range of isotopic values, and significantly different isotopic variance in the Formative Period relative to the Archaic. Also, overall changes in nitrogen isotope values indicate less reliance on marine resources than in the preceding Archaic (Andrade et al., 2015; King et al., 2018a; Pestle et al., 2015). Recent work on shell middens at Caleta Vitor (~30km south of Arica) has shown that, although marine resources were still heavily relied upon through periods of environmental change, the composition of species exploited changed significantly (Santoro et al., 2017) with ENSO linked fluctuations of water temperature. The cyclic nature of resource availability and use may also explain the variation in dietary isotope values within single sites (as per King et al.,

2018a). If people at different times are using different levels of terrestrial vs. marine resources this will result in high levels of variance in bone collagen values.

Our paleopathological data shows that this dietary variability was accompanied by a significant increase in scurvy suggesting a decrease in dietary quality and diversity. Furthermore, the presence of subperiosteal new bone in the suite of scorbutic lesions observed is indicative of cyclic or periodic vitamin C deficiency as at least some dietary ascorbic acid must have been restored before death for these lesions to form. This suggests periodic resource scarcity: the pattern expected to be associated with cyclic resource depletion. We posit that this pattern may be related to extreme El Niño events, where high vitamin C foods became less available due to temporary depression of the fisheries. We, therefore, believe that our framework has merit and that this pattern of variable isotopic values and evidence for periodic deficiencies might be linked to El Niño events. We suggest that further paleopathological work in the wider Atacama may reveal that this pattern is a region-wide trend indicative of resource vulnerability during times of intense ENSO activity.

Our model emphasizes the connection between environment, biology, and culture. 'Local biologies' theory suggests that human biology is reliant on both local environmental and socio-cultural conditions (Blom & Knudson 2019; Lock 1993). In the Atacama, it is easy to rely on purely environmental explanations for cultural and biological change. However, environmental change may be buffered or exacerbated by human social responses. In this study region, we suggest that environmental conditions likely precipitated localized resource scarcity and micronutrient famines but the maintenance of a broad subsistence base provided an adaptive social response to this vulnerability.

The relationship between resource stress and Vitamin C intake in the northern Atacama

Marine resources (with high $\delta^{15}N$), particularly the skin and organs of marine mammals, have generally higher vitamin C content, while the lower trophic level terrestrial staple foods cultivated here (e.g. maize, quinoa) contain negligible amounts of this micronutrient. We suggest that during El Niño years, horticulturalists in the Formative Period Atacama may have become nearly exclusively reliant on the success of supplementary domesticates which are relatively high in vitamin C (e.g. capsicum, squash, sweet potato). However, even during relatively 'wet' El Niño periods the harsh environment of the region may well have been incapable of producing enough of these resources to offset the decreased marine harvest, leading to periodic micronutrient famines.

Consideration of ethnographic data of contemporary human groups who employ a similar subsistence strategy to the Archaic Period Chinchorro may further clarify the relationship between the heavy exploitation of marine foods and vitamin C intake. For example, scurvy is extraordinarily rare among the Inuit of Alaska, Northern Canada, and Greenland, although prior to the introduction of "Southern" foods these people consumed very few terrestrial resources for most of the year and relied almost exclusively on marine organisms (Denniston, 1974; Draper, 1977). The tissues of marine mammals (i.e. seal, porpoise, etc.), particularly the skin and organs, are rich in ascorbic acid (Draper, 1977; Fediuk et al., 2002). These tissues are consumed raw or minimally cooked in the traditional Inuit diet which conserves their vitamin C content (Draper, 1977). This comparison suggests that an exclusively marine hunter-gatherer economy may have been better able to meet the micro-nutritional needs of these individuals in an environment incapable of sustaining large-scale agricultural production of vitamin C rich-foods than the more terrestrial-focused diet of the Formative Period. However, as no material culture data exists on the processing of these resources in the Archaic and Formative Periods it is difficult to know how much of the naturally occurring ascorbate content was preserved in the consumed product.

Comparison to the agricultural transition elsewhere

The Archaic-Formative transition in the Northern Chilean Atacama involved significant biosocial changes that may have included decreased dietary quality and an increase in associated nutritional deficiencies. Yet certain trends associated with both subsistence transitions and environmental change in other parts of the world do not seem to be present in the northern Chilean Atacama. For example, isotopic variability in the Formative Period suggests that diet does not shift wholesale to farmed resources, but instead becomes a mixed and variable form of subsistence incorporating both marine hunting and gathering and agricultural strategies (e.g. King et al., 2018a; Pestle et al., 2015). This result should not be wholly unexpected: flexibility can be a social response to resource vulnerability and is an adaption that leads to population resilience (Turner et al., 2003). It seems likely that in the northern Atacama a generalist subsistence was an important social strategy for survival.

In this region other "typical" social trends associated with agriculture also may not be occurring. Changes to weaning and fertility, including the shortening of breastfeeding period, for example, are not obvious. Weaning behavior appears to be variable throughout prehistory here (King et al., 2018b), with both marine resources and agricultural staples used as complementary resources (King et al., 2018b; Smith et al., 2017). This suggests that the marine hunter-gatherers of the Archaic also had access to suitable weaning foods (i.e. fish) and did not require agricultural staples to begin early initiation of weaning. Consideration of modern Andean ethnographic data on child feeding practices, particularly during times of resource stress, may be useful (Leonard, 1991). Additional paleoepidemiological work across the transition incorporating osseous markers of infectious disease and non-specific stress indicators may also help to elucidate this further.

The discrepancies between changes in health modeled elsewhere in the world, and those observed in the Atacama highlight the complexity of human-environmental adaptations (e.g. Zaro et al., 2008). As with any model, more data is needed to establish whether the trends we have identified are present throughout the northern Atacama Desert, or whether they are specific to the Arica area. Although isotopic research in the region is quite well-established, osteological investigation of nutritional deficiencies and their relationship with dietary and environmental change is less common. However, new diagnostic techniques are emerging which may enable researchers to examine whether or not specific micro-nutritional deficiencies are present within a population (e.g. Brickley, 2018; Snoddy et al., 2018).

Further testing of the model

Perhaps most importantly, there needs to be improved chronological control for sites and burials, allowing better time resolution and assessment of whether trends are linked to specific ENSO events. Kintigh and Ingram (2017) have recently highlighted the importance of robust dating of both climatic events and cultural transitions in the exploration of the biosocial effects of environmental change in the past. Currently, many skeletal collections associated with the Archaic-Formative transition are either minimally radiocarbon dated, or dated purely through material culture seriation. Additionally, sampling the tissues of individuals with a high marine dietary component substantially increases the confidence interval associated with radiocarbon dates through the marine reservoir effect (Ascough et al., 2005) and this has certainly influenced the dating of the sites in this study. If, as we suspect, diet is changing over short period, better temporal resolution is required to examine how well dietary choices are correlated with large or catastrophic ENSO events. Ideally, we should be identifying individuals who lived through extreme El Niño years to examine their dietary coping strategies through those periods. It is now possible to perform serial analysis of

gradually growing tissues such as hair (Webb et al., 2015) and dentin (Beaumont et al., 2015) to establish how conditions changed during the period of their formation. The analysis of climate/precipitation related isotopes (e.g. $\delta^{18}O$ in dentinal phosphate, or δD in collagen or keratin) analyzed alongside dietary isotopes from the same tissue could allow us to directly assess dietary responses to climatic changes within a single lifetime.

Conclusion

Marginal environments such as the Atacama are unique in their sensitivity to even slight changes in climate. Because of this, paradigms of the health impacts of climate change both today and in the past need to account for variation in regional ecologies. This paper has developed a new model for how archaeologically visible outcomes of climate instability might be assessed. In testing this model, we have provided new evidence for increased micro-nutritional stress across the Archaic-Formative transition in the Ancient Atacama Desert occurring in tandem with increased ENSO activity in the paleoclimatic record and isotopic evidence of a shift towards terrestrial resource use. We have interpreted our findings through the lens of human biological responses to environmental change and propose that the onset of more frequent ENSO events resulted in cyclical terrestrial and marine resource use leading to periodic micro-nutrient 'famines'. However, we acknowledge that more work, particularly in increasing the chronological resolution of archaeological sites in this region and incorporating other skeletal markers of nutritional stress, is necessary to ground-truth this model.

References

Acsádi, G. & Nemeskéri, J. (1970). *History of human life span and mortality*. Budapest: Akadémiai Kiadó.

Allison, M. J. (1984). Paleopathology in Peruvian and Chilean populations. In M.N. Cohen & G.J. Armelagos (Eds.) *Paleopathology at the origins of agriculture,* (pp. 515-529). Gainsville: University Press of Florida.

Andrade, P., Fernandes, R., Codjambassis, K., Urrea, J., Olguin, L., Rebolledo, S., Lira, F., Aravena, C., & Berríos, M. (2015). Subsistence continuity linked to consumption of marine protein in the Formative Period in the interfluvic coast of northern Chile: Re-assessing contacts with agropastoral groups from highlands. *Radiocarbon*, *57*(4), 679–688. DOI:10.2458/azu_rc.57.18448

Andrade, P. & Castro, V. (2016). Reconstrucción del modo de vida de endividuos del arcaico de la costa Arreica del Norte de Chile: Una aproximación bioarqueológica desde el sitio Copaca 1. *Chungara: Revista De Antropología Chilena, 48*(1), 73-90.

Arriaza, B. T., Standen, V. G., Belmonte, E., Rosello, E., & Nials, F. (2001). The peopling of the Arica coast during the precermaic: A preliminary view. *Chungara: Revista De Antropología Chilena, 33*(1), 31–36. DOI:10.2307/27802158

Arriaza, B. T., Standen, V.G., Cassman, V., & Santoro, C.M. (2008). Chinchorro culture: Pioneers of the coast of the Atacama Desert. In H. Silverman & W. H. Isbell (Eds.), *The handbook of South American archaeology* (pp. 45–58). New York: Springer.

Ascough, P., Cook, G., & Dugmore, A. (2005). Methodological approaches to determining the marine radiocarbon reservoir effect. *Progress in Physical Geography: Earth and Environment*, *29*(4), 532–547. DOI:10.1191/0309133305pp461ra

Aufderheide, A. C., Muñoz, I., & Arriaza, B. T. (1993). Seven Chinchorro mummies and the prehistory of Northern Chile. *American Journal of Physical Anthropology, 91*(2), 189–201.

Aufderheide, A. C., Kelley, M. A., Rivera, M., Gray, L., Tieszen, L. L., Iversen, E., Krouse, R.H., & Carevic, A. (1994). Contributions of chemical dietary reconstruction to the assessment of adaptation by ancient highland immigrants (Alto Ramirez) to coastal conditions at Pisagua, north Chile. *Journal of Archaeological Science, 21*(4), 515–524. DOI:10.1006/jasc.1994.1051

Aufderheide, A. C., Aturaliya, S., & Focacci, G. (2002). Pulmonary disease in a sample of mummies From the AZ-75 cemetery in northern Chile's Azapa Valley. *Chungara: Revista De Antropología Chilena, 34*(2), 253–63. DOI:10.2307/27802220.

Beaumont, J., Montgomery, J., Buckberry, J., & Jay, M. (2015). Infant mortality and isotopic complexity: New approaches to stress, maternal health, and weaning. *American Journal of Physical Anthropology*, *157*(3), 441–457. DOI:10.1002/ajpa.22736

Berger, E., & Wang, H. (2017). Bioarchaeology of adaptation to a marginal environment in bronze age Western China. *American Journal of Human Biology*, *29*(4), e22956.

Blom, D. E., & Knudson, K. J. (2019). Paleopathology and children in the Andes: Local/situated biologies and future directions. *International Journal of Paleopathology, Early view*. DOI: 10.1016/j.ijpp.2019.08.004.

Brickley, M. & Ives, R. (2008). *The bioarchaeology of metabolic bone disease*. New York: Academic Press.

Brickley, M. B. (2018). Cribra orbitalia and porotic hyperostosis: A biological approach to diagnosis. *American Journal of Physical Anthropology, 153*(10), 760–67. DOI:10.1002/ajpa.23701.

Brooks, S.T. & Suchey, J. M. (1990). Skeletal age determination based on the os pubis: A comparision of the Acsádi-Nemskéri and Suchey-Brooks methods. *Human Evolutuion, 5*, 227-238.

Buckley, H. R., Kinaston, R. L., Halcrow, S. E., Foster, A., Spriggs, M, & Bedford, S. (2014). Scurvy in a tropical paradise? Evaluating the possibility of infant and adult vitamin C deficiency in the Lapita skeletal sample of Teouma, Vanuatu, Pacific Islands. *International Journal of Paleopathology, 5*, 72–85. DOI:10.1016/j.ijpp.2014.03.001.

Buikstra, J. E. & Ubelaker, D. H. (1994). *Standards for data collection in human skeletal remains*. Fayetteville: Arkansas Archaeological Survey.

Caldwell, P. (1996). Child survival: Physical vulnerability and resilience in adversity in the European past and the contemporary Third World. *Social Science & Medicine, 43*(5), 609–19. DOI:10.1016/0277-9536(96)00109-8.

Cereceda, P., Larrain, H., Osses, P., Farías, M, & Egaña, I. (2008a). The climate of the coast and fog zone in the Tarapacá region, Atacama Desert, Chile. *Atmospheric Research, 87*(3-4): 301–11. DOI:10.1016/j.atmosres.2007.11.011.

Cereceda, P., Larrain, H., Osses, P., Farías, M., & Egaña, I. (2008b). The spatial and temporal variability of fog and its relation to fog oases in the Atacama Desert, Chile. *Atmospheric Research, 87*(3-4), 312–23. DOI:10.1016/j.atmosres.2007.11.012.

Cheung, E., Mutahar, R., Assefa, F., Ververs, M-T, Nasiri, S. M., Borrel, A., & Salama, P. (2003). An epidemic of scurvy in Afghanistan: Assessment and response. *Food and Nutrition Bulletin, 24*(3), 247–55.

Clarke, J. D. A. (2006). Antiquity of aridity in the Chilean Atacama Desert. *Geomorphology, 73*(1-2), 101–14. DOI:10.1016/j.geomorph.2005.06.008.

Crandall, J. J. (2014). Scurvy in the greater American southwest: Modeling micronutrition and biosocial processes in contexts of resource stress. *International Journal of Paleopathology 5*, 46–54. DOI:10.1016/j.ijpp.2014.05.001.

de Bryson, R., Luz, M., Bryson, R. U., & Bryson, R. A. (2001). Paleoclimatic and material cultural perspective on the Formative Period of northern Chile. *Chungara: Revista De Antropología Chilena*, *33*(1), 5–12.

Denniston, G. B. (1974). The diet of the ancient inhabitants of Ashishik point, an Aleut community. *Arctic Anthropology*, *11*, 143–152. DOI:10.2307/40315808

Díaz-Zorita Bonilla, M., Drucker, D. G., Richardin, P., Silva-Pinto, V., Sepúlveda, M., & Bocherens, H. (2016). Marine food consumption in coastal northern Chilean (Atacama Desert) populations during the Formative Period: Implications of isotopic evidence (C, N, S) for the Neolithic process in south central Andes. *Journal of Archaeological Science: Reports, 6*, 768–76. DOI:10.1016/J.JASREP.2016.01.026.

Dilley, M., & Heyman, B. (1995). ENSO and disaster: droughts, floods, and El Niño/ Southern Oscillation warm events. *Disasters, 19*, 181–93.

do Nascimento, V. T., da Silva Vasconcelos, M. A., Maciel, M. I. S., & Albuquerque, U. P. (2012). Famine foods of Brazil's seasonal dry forests: Ethnobotanical and nutritional aspects. *Economic Botany*, *66*(1), 22–34. DOI:10.1007/s12231-012-9187-2

Draper, H. H. (1977). The aboriginal Eskimo diet in modern perspective. *American Anthropologist*, *79*(2), 309–316. DOI:10.1525/aa.1977.79.2.02a00070

Fazekas, I. G. & Kósa, F. (1978). *Forensic fetal osteology*. Budapest: Akadémiai Kiadó.

Fediuk, K., Hidiroglou, N., Madère, R., & Kuhnlein, H. V. (2002). Vitamin C in Inuit traditional food and women's diets. *Journal of Food Composition and Analysis, 15*(3), 221–35. DOI:10.1006/jfca.2002.1053.

Focacci, G. A., & Chacón, S. C. (1989). Excavaciones arqueologicas en los Faldos del Morro de Arica sitios Morro 1/6 y 2/2. *Chungara: Revista De Antropología Chilena*, *22*, 15–62.

Focacci, G. & Erices, S.C. (1973). Excavaciones en tumulos de San Miguel de Azapa. *Actas del VI Congreso de Arqueología Chilena*. (pp. 47-55) Santiago: Universidad de Chile

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., & Hedges, R. E. M. (2005). Nitrogen balance and $\delta^{15}N$: why you're not what you eat during nutritional stress. *Rapid Communications in Mass Spectrometry*, *19*(18), 2497–2506. DOI:10.1002/rcm.2090

Gayo, E. M., Latorre, C., Santoro, C. M., Maldonado, A., & De Pol-Holz, R. (2012). Hydroclimate variability in the low-elevation Atacama Desert over the last 2500 yr. *Climate of the Past, 8*(1), 287–306. DOI:10.5194/cp-8-287-2012.

Geber, J., & Murphy, E. (2012). Scurvy in the great Irish famine: Evidence of vitamin C deficiency from a mid-19th century skeletal population. *American Journal of Physical Anthropology*, *148*(4), 512–524. DOI:10.1002/ajpa.22066

Glantz, M.H. (2001). *Currents of change: Impacts of El Niño and La Niña on climate and society*. Cambridge: Cambridge University Press.

Geraci, J. R. & Smith, T. G. (1979). Vitamin C in the diet of Inuit hunters from Holman, northwest territories. *Arctic, 32*(2), 135–39. DOI:10.2307/40508955

Grivetti, L. E., & Ogle, B. M. (2009). Value of traditional foods in meeting macro- and micronutrient needs: the wild plant connection. *Nutrition Research Reviews*, *13*(01), 31–16. DOI:10.1079/095442200108728990

Guilyardi, E. (2005). El Niño–mean state–seasonal cycle interactions in a multi-model ensemble. *Climate Dynamics, 26*(4), 329–48. DOI:10.1007/s00382-005-0084-6.

Halcrow, S. E., & Tayles, N. (2008). The bioarchaeological investigation of childhood and social age: problems and prospects. *Journal of Archaeological Method and Theory*, *15*(2), 190–215.

Hesse, B. (1984). Archaic exploitation of small mammals and birds in northern Chile. *Estudios Atacameños, 7*, 37–51.

Holden, T. G. (1994). Dietary evidence from the intestinal contents of ancient humans with particular reference to desiccated remains from northern Chile. I J. G. Hather (ed.) *Tropical archaeobotany: Applications and new developments*. (pp 66-85) London: Routledge.

Houston, J. (2006a). The great Atacama flood of 2001 and its implications for Andean hydrology. *Hydrological Processes, 20*(3), 591–610. DOI:10.1002/hyp.5926.

Houston, J. (2006b). Variability of precipitation in the Atacama Desert: Its causes and hydrological impact. *International Journal of Climatology, 26*(15), 2181–98. DOI:10.1002/joc.1359.

Houston, J. (2006c). Evaporation in the Atacama Desert: an empirical study of spatio-temporal variations and their causes. *Journal of Hydrology, 330*(3-4), 402–12. DOI:10.1016/j.jhydrol.2006.03.036.

Huss-Ashmore, R. & Goodman, A. H. (1982). Nutritional inference from paleopathology. *Advances in Archaeological Method and Theory, 5*, 395–474. DOI:10.2307/20210060.

Jaksic, F. M. (2001). Ecological effects of El Niño in terrestrial ecosystems of western South America. *Ecography, 24*(3), 241–50. DOI:10.1034/j.1600-0587.2001.240301.x.

Kane, P. (1987). The demography of famine. *Genus, 43*(1-2), 43–58.

Kiladis, G. N. & Diaz, H. F. (1989). Global climatic anomalies associated with extremes in the southern oscillation. *Journal of Climate, 2*(9), 1069–90.

King, C. L., Millard, A. R., Gröcke, D. R., Standen, V. G., Arriaza, B. T., & Halcrow, S. E. (2018a). Marine resource reliance in the human populations of the Atacama Desert, northern Chile - A view from prehistory. *Quaternary Science Reviews*, *182*, 163–174. DOI:10.1016/j.quascirev.2017.12.009

King, C. L., Halcrow, S. E., Millard, A. R., Gröcke, D. R., Standen, V. G., Portilla, M., & Arriaza, B. T. (2018b). Let's talk about stress, baby! Infant-feeding practices and stress in the ancient Atacama desert, Northern Chile. *American Journal of Physical Anthropology*, *166*(1), 139-155. DOI:10.1002/ajpa.23411

Kintigh, K. W., & Ingram, S. E. (2018). Was the drought really responsible? Assessing statistical relationships between climate extremes and cultural transitions. *Journal of Archaeological Science*, *89*, 25–31. DOI:10.1016/j.jas.2017.09.006

Klaus, H. D. (2014). Subadult scurvy in Andean South America: Evidence of vitamin C deficiency in the late pre-Hispanic and colonial Lambayeque valley, Peru. *International Journal of Paleopathology, 5*, 34-45. DOI:10.1016/j.ijpp.2013.09.002.

Klaus, H. D. (2017). Paleopathological rigor and differential diagnosis: Case studies involving terminology, description, and diagnostic frameworks for scurvy in skeletal remains. *International Journal of Paleopathology, 19*, 96–110. DOI:10.1016/j.ijpp.2015.10.002.

Knudson, K. J., Torres-Rouff, C., & Stojanowski, C. M. (2015). Investigating human responses to political and environmental change through paleodiet and paleomobility. *American Journal of Physical Anthropology*, *157*(2), 179–201. DOI:10.1002/ajpa.22694

Kovats, R. S., Bouma, M. J., Hajat, S., Worrall, E. & Haines, A. (2003). El Niño and health. *The Lancet 362*(9394), 1481–89. DOI:10.1016/S0140-6736(03)14695-8.

Langstroth, R. P. (2011). On the species identities of a complex Liolaemus fauna from the Altiplano and Atacama Desert: Insights on Liolaemus stolzmanni, L. reichei, L. jamesi pachecoi, and L. poconchilensis (squamata: Liolaemidae). *Zootaxa, 2809*(April), 20–32.

Latorre, C., Betancourt, J. L., Rylander, K. A., Quade, J., & Matthei, O. (2003). A vegetation history From the arid prepuna of northern Chile (22–23°S) over the last 13500 years. *Palaeogeography, Palaeoclimatology, Palaeoecology, 194*(1-3), 223–46. DOI:10.1016/S0031-0182(03)00279-7.

Leonard, W. R. (1991). Household-level strategies for protecting children from seasonal food scarcity. *Social Science & Medicine*, *33*(10), 1127–1133.

Levine, M. & Padayatty, S. J. (2014). Vitamin C. In C. A. Ross (Ed.) *Modern nutrition in health and disease* (pp. 399-419). Philadelphia: Wolters Kluwer.

Lewis, M. (2007). *The bioarchaeology of children: Perspectives from biological and forensic anthropology.* New York: Cambridge University Press.

Lewis, M. (2018). *Paleopathology of children: Identification of pathological conditions in the human skeletal remains of non-adults*. London: Academic Press.

Lioubimtseva, E. & Henebry, G. M. (2009). Climate and environmental change in arid central Asia: Impacts, vulnerability, and adaptations. *Journal of Arid Environments, 73*(11), 963–77. DOI:10.1016/j.jaridenv.2009.04.022.

Lock, M. (1993). Cultivating the body: Anthropology and epistemologies of bodily practice and knowledge. *Annual Review of Anthropology, 22*(1), 133–55. DOI:10.1146/annurev.an.22.100193.001025.

Lockett, C. T., Calvert, C. C., & Grivetti, L. E. (2009). Energy and micronutrient composition of dietary and medicinal wild plants consumed during drought. Study of rural Fulani, Northeastern Nigeria. *International Journal of Food Sciences and Nutrition*, *51*(3), 195–208. DOI:10.1080/09637480050029700

Magilligan, F. J., Goldstein, P. S., Fisher, G. B., Bostick, B. C., & Manners, R. B. (2008). Late Quaternary hydroclimatology of a hyper-arid Andean watershed: Climate change, floods, and hydrologic responses to the El Niño-Southern Oscillation in the Atacama Desert. *Geomorphology, 101*(1-2), 14–32. DOI:10.1016/j.geomorph.2008.05.025.

Maresh, M.M. (1970). Measurements from roentgenograms. In R.W. McCammon (ed.) *Human growth and development* (pp. 157-200). Springfield: Charles C. Thompson.

Marquet, P. A., Santoro, C. M, & Latorre, C. (2012). Emergence of social complexity among coastal hunter-gatherers in the Atacama Desert of northern Chile. *Proceedings of the National Academy of Science, 109*, 14754–60. DOI:10.1073/pnas.1116724109/-/DCSupplemental.

Meindl, R.S. & Lovejoy, C.O. (1989). Age changes in the pelvis: Implications for paleodemography. In M.Y. Işcan (ed.), *Age markers in the human skeleton* (pp. 137-168). Springfield: Charles C. Thomas.

Miloslavich, P., Klein, E., Díaz, J. M., Hernández, C. E., Bigatti, G., Campos, L., Artigas, F., Castillo, J., Penchaszadeh, P. E., Neill, P. E., Carranza, A., Retana, M. V., Diaz, De Astarloa, J. M., Lewis, M., Yorio, P., Piriz, M. L., Rodriguez, D., Yoneshigue - Valentin, Y., Gamboa, L., Martin, A. (2011). Marine biodiversity in the Atlantic and Pacific coasts of South America: Knowledge and gaps. *PLOS ONE, 6*(1), e14631–43. DOI:10.1371/journal.pone.0014631.

Montecino, V. & Lange, C. B. (2009). The Humboldt current system: Ecosystem components and processes, fisheries, and sediment studies. *Progress in Oceanography, 83*(1-4), 65–79. DOI:10.1016/j.pocean.2009.07.041.

Mora, A., Arriaza, B. T., Standen, V. G., Valdiosera, C., Salim, A., & Smith, C. (2017). High-resolution palaeodietary reconstruction: Amino acid $\delta^{13}C$ analysis of keratin from single hairs of mummified human individuals. *Quaternary International*, *436*, 96–113. DOI:10.1016/j.quaint.2016.10.018

Moreno, A., Santoro, C. M., & Latorre, C. (2009). Climate change and human occupation in the northernmost Chilean Altiplano over the last ca. 11 500 cal. a BP. *Journal of Quaternary Science*, *24*(4), 373–382. DOI:10.1002/jqs.1240.

Moreno, S., Engel, F. R., & Aspillaga, E. F. (1992). Paleodemografía en momias de poblaciones prehispánicas de Arica. *Revista Médica de Chile*, *120*, 735–740.

Muller, J., & Almedom, A. M. (2008). What is "famine food?" Distinguishing between traditional vegetables and special foods for times of hunger/scarcity (Boumba, Niger). *Human Ecology*, *36*(4), 599–607. DOI:10.1007/s10745-008-9179-0

Muñoz, I. O. (1980). Investigaciones arqueológicas en los túmolos funerarios del Valle de Azapa (Arica). *Chungara: Revista De Antropología Chilena*, *6*, 57–95.

Muñoz, I. O. (1987). Enterramientos en túmulos en el Valle de Azapa: Neuvas evidencias para definir la fase Alto Ramirez en el exremo norte de Chile. *Chungara: Revista De Antropología Chilena*, *19*, 93–127.

Muñoz, I., & Chacama, R.J. (2012). Transformación del paisaje social en Arica, norte de Chile: De pescadores Arcaicos a agricultores incipientes. *Estudios Atacameños 44*, 123–40. DOI:10.4067/S0718-10432012000200007.

Muñoz, I., & Gordillo, J. (2016). Organización del espacio y uso de los recursos naturales en la conformación de aldeas y campamentos en el período Medio en los valles de Azapa, Norte de Chile y Caplina, Sur del Perú. *Chungara Revista de Antropología Chilena 48*, 531-555.

Núñez, L. (1986). Evidencias arcaicas de maíces y cuyes en Tiliviche: Hacia el semisedentarismo en el litoral fértil y quebradas del Norte de Chile. *Chungara Revista de Antropología Chilena, 16*, 25-47.

Núñez, L., & Santoro, C.M. (2011). El transito Arcaico-Formativo en la circumpuna y valles occidentales del centro sur Andino: hacia los cambios "Neolíticos". *Chungara: Revista De Antropología Chilena, 43*, 487-530.

Ortner, D. J., Kimmerle, E. H., & Diez, M. (1999). Probable evidence of scurvy in subadults from archeological sites in Peru. *American Journal of Physical Anthropology, 108*(3), 321–31.

Ortner, D.J. (2003). *Identification of pathological conditions in human skeletal remains* New York: Academic Press.

Peña-Torres, J. & Basch, M. (2000). Harvesting in a pelagic fishery: The case of northern Chile. *Annals of Operations Research, 94*(1), 295–320.

Pestle, W. J., Torres-Rouff, C., Hubbe, M., Santana S, F., Pimentel, G., Gallardo, F., & Knudson, K. J. (2015). Explorando la diversidad dietética en la prehistoria del desierto de Atacama: Un acercamiento a los patrones regionales. *Chungara: Revista De Antropología Chilena*, *47*(2), 201–209. http://doi.org/10.4067/S0717-73562015005000013

Petruzzelli, B., Roberts, A., Pate, F. D., Santoro, C. M., Maddern, T., Carter, C., & Westaway, M. (2012). Stable carbon and nitrogen isotopic analysis of skeletal remains from Azapa 71 and Pica-8, northern Chile: An assessment of human diet and landscape use in the late Holocene. *Journal of the Anthropological Society of South Australia*, *35*, 52-80.

Phenice, T.W. (1969). A newly developed visual method of sexing in the os pubis. *American Journal of Physical Anthropology, 30*, 297-301.

Poulson, S. R., Kuzminsky, S. C., Scott, G. R., Standen, V. G., Arriaza, B., Muñoz, I., & Dorio, L. (2013). Paleodiet in northern Chile through the Holocene: extremely heavy δ^{15}N values in dental calculus suggest a guano-derived signature? *Journal of Archaeological Science*, *40*(12), 4576–4585. DOI:10.1016/j.jas.2013.07.009

R core team, (2013). *R: A language and environment for statistical computing.* Vienna: R foundation for statistical computing.

Reinhard, K. J., LeRoy-Toren, S., & Arriaza, B. T. (2011). Where have all the plant foods gone? The search for refined dietary reconstruction from Chinchorro mummies. *Yearbook of Mummy Studies*, *1*, 139–151.

Reitsema, L. J. (2013). Beyond diet reconstruction: Stable isotope applications to human physiology, health, and nutrition. *American Journal of Human Biology*, *25*(4), 445–456. DOI:10.1002/ajhb.22398

Robbins-Schug, G. (2011). *Bioarchaeology and climate change: A view from south Asian prehistory*. Gainsville: University Press of Florida.

Robbins-Schug, G. & Blevins, K. E. (2016). The center cannot hold: a bioarchaeological perspective on environmental crisis in the second millennium. In G. Robbins Schug & S. R. Walimbe (Eds.), *A Companion to South Asia in the Past* (pp. 255–73). West Sussex: John Wiley & Sons.

Roberts, A., Pate, F. D., Petruzzelli, B., Carter, C., Westaway, M. C., Santoro, C. M., Swift, J., Maddern, T., Jacobsen, G. E., Bertuch, F., & Rothhammer, F. (2013). Retention of hunter-gatherer economies among maritime foragers from Caleta Vitor, northern Chile, during the late Holocene: Evidence from stable carbon and nitrogen isotopic analysis of skeletal remains. *Journal of Archaeological Science*, *40*(5), 2360–2372. DOI:10.1016/j.jas.2013.01.009

Rothhammer, F., Santoro, C. M., Poulin, E., Arriaza, B. T., Moraga, M., & Standen, V. J., (2009). Archeological and mtDNA evidence for tropical lowland migrations during the late Archaic/Formative in northern Chile. *Revista Chilena de Historia Natural, 82* (4), 543–52. DOI:10.4067/S0716-078X2009000400008.

Rundel, P. W., Villagra, P.E., Dillon, M.O., Roig-Juñent, S. & Debandi G. (2007). Arid and semi-arid ecosystems. In T.T. Veblen, K.R. Young, & A.R. Orme (Eds.), *The physical geography of South America* (pp. 158-183). New York: Oxford University Press.

Sandweiss, D. H., Maasch, K. A., & Burger, R. L. (2001). Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru. *Geology, 29*, 603–606.

Sandweiss, D. H., Maasch, K. A., Fei Chai, C., Andrus, F. T., & Reitz, E. J. (2004). Geoarchaeological evidence for multidecadal natural climatic variability and ancient Peruvian fisheries. *Quaternary Research, 61*(3), 330–34. DOI:10.1016/j.yqres.2004.02.008.

Santana-Sagredo, F., Uribe, M., Herrera, M. J., Retamal, R., & Flores, S. (2015). Brief communication: Dietary practices in ancient populations from northern Chile during the transition to agriculture (Tarapacá region, 1000 BC-AD 900). *American Journal of Physical Anthropology*, *158*(4), 751–758. DOI:10.1002/ajpa.22826

Santoro, C. M. (1980a). Fase Azapa, transición del Arcaico al desarrollo agrario inicial en los valles bajos de Arica. *Chungara: Revista De Antropología Chilena*, *6,* 46–56.

Santoro, C. M. (1980b). Estratigrafía y secuencia cultural funeraria fases: Azapa, Alto Ramírez y Tiwanaku (Arica - Chile). *Chungara: Revista De Antropología Chilena*, *6*, 24–45.

Santoro, C. M. (1982). Formativo temprano en al extremo norte de Chile. *Chungara: Revista De Antropología Chilena*, *8*, 33–62.

Santoro, C. M., Arriaza, B. T., Standen, V. G., & Marquet, P. A. (2005). People of the coastal Atacama Desert: Living between sand dunes and waves of the Pacific Ocean. In P. Veth, M.

Smith, & P. Hiscock (Eds.), *Desert peoples: Archaeological perspectives* (pp. 243–260). Oxford: Wiley Blackwell.

Santoro, C. M., Gayo, E. M., Carter, C., Standen, V. G., Castro, V., Valenzuela, D., De Pol-Holtz, R., Marquet, P. A., & Latorre, C. (2017). Loco or no loco? Holocene climatic fluctuations, human demography, and community based management of coastal resources in northern Chile. *Frontiers in Earth Science*, *5*, 474–16. DOI:10.3389/feart.2017.00077

Scheuer, L. & Black, S. (2000). *Developmental juvenile osteology*. Oxford: Elsevier.

Seo, S. N., & Mendelsohn, R. (2008). An analysis of crop choice: Adapting to climate change in South American farms. *Ecological Economics*, *67*(1), 109–116. DOI:10.1016/j.ecolecon.2007.12.007

Sepúlveda, S. A., Rebolledo, S., McPhee, J., Lara, M., Cartes, M., Rubio, E., Silva, D., Correia, N., & Vásquez, J. P. (2014). Catastrophic, rainfall-induced debris flows in Andean villages of Tarapacá, Atacama Desert, northern Chile. *Landslides, 11*(3), 481–91. DOI:10.1007/s10346-014-0480-2.

Smith, E. K., Pestle, W. J., Clarot, A., & Gallardo, F. (2017). Modeling breastfeeding and weaning practices (BWP) on the coast of northern Chile's Atacama Desert during the Formative Period. *The Journal of Island and Coastal Archaeology*, *12*(4), 558–571. DOI:10.1080/15564894.2016.1253047

Snoddy, A. M. E., Halcrow, S. E., Buckley, H. R., Standen, V. G., & Arriaza, B. T. (2017). Scurvy at the agricultural transition in the Atacama Desert (ca 3600–3200 BP): Nutritional stress at the maternal-foetal interface?. *International Journal of Paleopathology, 18*(June), 108–20. DOI:10.1016/j.ijpp.2017.05.011.

Snoddy, A. M. E., Buckley, H. R., Elliott, G. E., Standen, V. G., Arriaza, B. T., & Halcrow, S. E. (2018). Macroscopic features of scurvy in human skeletal remains: a literature synthesis and diagnostic guide. *American Journal of Physical Anthropology, 5*(October), 967–20. DOI:10.1002/ajpa.23699.

Standen, V.G. (2003). Bienes funeratios del cementerio Chinchorro Morro 1: Descripción, análisis e interpretación. *Chungara: Revista De Antropología Chilena, 35*(2), 175-207.

Standen, V. G., & Sanhueza, J. (1984). Análisis antropológico físico del cementerio Mocha 2 (norte de Chile, I región). *Estudios Atacameños, 7*, 237–242.

Standen, V. G., Arriaza, B. T., & Santoro, C. M. (1997). External auditory exostosis in prehistoric Chilean populations: A test of the cold water hypothesis. *American Journal of Physical Anthropology*, *103*(1), 119–129.

Standen, V. G., Santoro, C. M., Arriaza, B. T., Coleman, D. (2018). Hunting, gathering, and fishing on the coast of the Atacama Desert: Chinchorro population mobility patterns inferred from strontium isotopes. *Geoarchaeology, 33*(2):162-176

Sutter, R. C., & Mertz, L. (2004). Nonmetric cranial trait variation and prehistoric biocultural change in the Azapa Valley, Chile. *American Journal of Physical Anthropology*, *123*(2), 130–145. DOI:10.1002/ajpa.10311

Tam, J., Taylor, M. H., Blaskovic, V., Espinoza, P., Ballón, M. R., Díaz, E., Wosnitza-Mendo, C., Argüelles, J., Purca, S., Ayón, P., Quipuzcoa, L., Gutiérrez, D., Goya, E., Ochoa, N., & Wolff, M. (2008). Trophic modeling of the northern Humboldt current ecosystem, part I: Comparing trophic linkages under La Niña and El Niño conditions. *Progress in Oceanography, 79*(2-4), 352–65. DOI:10.1016/j.pocean.2008.10.007.

Taylor, M. H., Tam, J., Blaskovic, V., Espinoza, P., Ballón, M. R., Wosnitza-Mendo, C., Argüelles, J., Díaz, E., Purca, S., Ochoa, N., Ayón, P., Goya, E., Gutiérrez, D., Quipuzcoa, L., & Wolff, M. (2008). Trophic modeling of the northern Humboldt current ecosystem, part II: Elucidating ecosystem dynamics from 1995 to 2004 with a focus on the impact of ENSO. *Progress in Oceanography, 79*(2-4), 366–78. DOI:10.1016/j.pocean.2008.10.008.

Tieszen, L.L., Iversen, E., & Matzner, S. (1995). Dietary reconstruction based on carbon, nitrogen, and sulfur stable isotopes in the Atacama Desert, northern Chile. In A. C. Aufderheide, & C. R. Martin (Eds.). *Proceedings of the world congress on mummy studies. Tenerife*. (p 427–41). Tenerife: Museo Arquelógico y Etnográfico de Tenerife.

Torres-Rouff, C., Pestle, W. J., & Gallardo, F. (2012). Eating fish in the driest desert in the world: Osteological and biogeochemical analyses of human skeletal remains from the San Salvador cemetery, north Chile. *Latin American Antiquity*, *23*(1), 51–69. DOI:10.7183/1045-6635.23.1.51

Tulchinsky, T.H. (2010). Micronutrient deficiency conditions: Global health issues. *Public Health Reviews 32*(1): 243–55. DOI:10.1007/BF03391600.

Turner, B. L., Kasperson, R.E., Matsone, P.A., McCarthy, J.J., Corell, R.W., Christensene, L., & Eckley, N. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences 100*(14): 8074–79. DOI:10.1073/pnas.1231335100.

Ubelaker, D.H. (1989). *Human skeletal remains (2nd ed).* Washington D.C.: Taraxacum Press.

USDA. (2019). *Food composition database*. United States Department of Agriculture. Retrieved 12/18/2018 from https://ndb.nal.usda.gov/ndb/search/list?home=true.

Walther, G-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J-M., Hoegh-Guldberg, O., & Bairlein, F. (2002). Ecological responses to recent climate change. *Nature, 416*(6879), 389–95. DOI:10.1038/416389a.

Webb, E. C., White, C. D., Van Uum, S., & Longstaffe, F. J. (2015). Integrating cortisol and isotopic analyses of archeological hair: Reconstructing individual experiences of health and stress. *American Journal of Physical Anthropology*, *156*(4), 577–594. DOI:10.1002/ajpa.22673

Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science*, *341*(6145), 508–513. DOI:10.1126/science.1239402

Whitford, W. & Wade, E. L. (2002). *Ecology of desert systems*. Cambridge, MA: Academic Press.

Williams, A., Santoro, C. M., Smith, M. A., & Latorre, C. (2008). The Impact of ENSO in the Atacama Desert and Australian arid zone: Exploratory time series analysis of archaeological records. *Chungara: Revista De Antropología Chilena, 40*(January), 245–59.

World Health Organization (WHO). (1999). *Scurvy and its prevention and control in major emergencies*. Geneva: World Health Organization.

Zaro, G., Builth, H., Rivera, C., Roldán, J., & Suvires, G. (2008). Landscape evolution and human agency: Archaeological case studies from drylands in western South America and Australia. *Chungara: Revista De Antropología Chilena*, *40*, 261–271. DOI:10.2307/27802524

Zhang, D. D., Brecke, P., Lee, H. F., He, Y-Q., & Zhang, J. (2007). Global climate change, war, and population decline in recent human history. *Proceedings of the National Academy of Sciences of the United States of America, 104*(49), 19214–19. DOI:10.1073/pnas.0703073104.