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Refining dietary shifts linked to climate oscillations in the Central Andes: stable isotope evidence from Vichama (1800–1500 BCE)

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The balance between fishing and farming for the development of complex societies in ancient Central Andes is the subject of a long debate. Despite the availability of marine resources in one of the world's richer marine ecosystems and the extreme aridity of the landscape, current evidence suggests that farming was the prime mover of early Andean civilization. In this study, we employed stable isotope analysis to reconstruct the diets of 38 human individuals from two occupations at Vichama, a coastal settlement with monumental architecture located in the Huaura Valley, Early Formative–1 period (EF-1, 1800–1500 BCE) and the Late Intermediate Period (LIP, 1000–1300 CE). Results show a considerable contribution of C₃ cultivated plants and marine protein during EF-1, which indicates the first importance of farming at that time, whereas marine consumption increased during the LIP, a period of higher marine productivity. Our findings shed light on the complex interplay between climate alternances and coastal/inland sites' hegemony in the Central Andes.

KEYWORDS

Andean formative period, dietary reconstruction, Bayesian stable isotope mixing models, climate change, Peruvian North-Central coast

Introduction

The connection between subsistence systems, climate oscillations, and social complexity has been extensively studied and documented for the Central Andes. Studies have shown that ancient Andean populations developed adaptive strategies modulated by ecological constraints since they arrived at the region ~14,000 years ago until the beginning of the Late Holocene (Dillehay, 2017; León, 2013; Piperno and Dillehay, 2008). Domesticated evidence dates to as early as 8000 BCE, and available data suggest that irrigation technologies supported plant cultivation by ~4500 BCE (Dillehay et al., 2005, 2007). Since ~3000 BCE, farming was the most important economic activity (Grobman et al., 2012; Yseki et al., 2023).

Increasing settlement size and distribution, shifts in domestic architecture, and the spatiotemporal modeling of demographic dynamics for the Peruvian coast indicate an exponential population growth between 2000 and 1 BCE (Goldberg et al., 2016).

The process has been attributed to a complex interplay between environmental changes and the expansion of agricultural regimes in the region (Contreras, 2010; Goldberg et al., 2016; Wilson et al., 2022).

In the last decades, a large volume of archaeological information has been produced for the Peruvian North-Central coast (PNCC), the epicenter of early complexity in the Central Andes (Creamer et al., 2013; Haas and Creamer, 2006; Makowski, 2023; Shady et al., 2001; Shady, 2018). Although pioneering evidence suggested that marine resources were the foundation of initial social complexity in this extremely challenging environment (Moseley, 1975), new evidence of plant consumption at coastal and middle valley monumental sites strongly indicates that farming was the subsistence system supporting the emergence of early civilization in the region (e.g., Caral civilization) and subsequent sociopolitical developments (Dillehay et al., 2007; Haas et al., 2013; Pezo-Lanfranco and Colonese, 2024; Shady, 2006a,b; Shoji et al., 2023; Tung et al., 2021).

In this area, studies suggest that coastal and inland societies would have been organized around symbiotic farming–fishing economies and littoral–inland trade networks since at least the Initial Formative (3000–1800 BCE), with coastal communities based on marine resources and some contribution of cultivated crops and inland groups relying in cultivated plants supplemented by marine products (Pezo-Lanfranco et al., 2022; Shady, 2018; Yseki et al., 2023).

This system, however, would have been influenced by the variability of sea surface temperatures (SSTs), upwelling dynamics, and productivity intensity in the Humboldt Current System (HCS), and El Niño Southern Oscillation (ENSO). The increase of SSTs produces a decrease in marine biomass, whereas in upper valleys, landslides increase as a consequence of intense rainfall, causing imponderable effects in farming production (Contreras, 2010). In the north and central coast of Peru, humid periods are linked to the prevalence of El Niño-like conditions, whereas La Niña-like conditions can be associated with dry and cold climate (Salvatteci et al., 2014, 2019; Leclerc, 2023).

Although the final causes and the complex mechanisms among the factors involved (e.g., ENSO teleconnections, Walker circulation intensity, meridional displacement of the Inter-Tropical Convergence Zone, and the South Pacific Subtropical High) are still in discussion (Mächtle and Eitel, 2013; Salvatteci et al., 2014, 2016; Scholz et al., 2014; Yseki et al., 2022), variations in SSTs, upwelling conditions, and productivity intensity in the HCS occurring on multiple timescales (Salvatteci et al., 2016, 2019; Yseki et al., 2022) likely had a significant impact on the availability and selection of marine resources utilized by past coastal communities and influenced the rise and decline of ancient Andean societies during the Holocene (Wilson et al., 2022, 2024). These effects occurred alongside persistent hazards, such as tectonic activity and geomorphological particularities (Orloff, 2022; Salvatteci et al., 2019; Sandweiss et al., 2009).

Export production refers to the fraction of organic carbon produced by photosynthetic organisms in the photic zone that is eventually deposited on the ocean floor; thus, it serves as a proxy for SST fluctuations in oceanography (Herbert, 2003; Scholz et al., 2014; Wefer et al., 2015). A comprehensive palaeoceanographic

study of the HCS based on high-resolution data (i.e., alkenone and bromide-to-titanium [Br/Ti] ratio) has revealed centennial-scale changes in SSTs and, in general, an increase in exported productivity from ~3000 to 1100 BCE (Salvatteci et al., 2019).

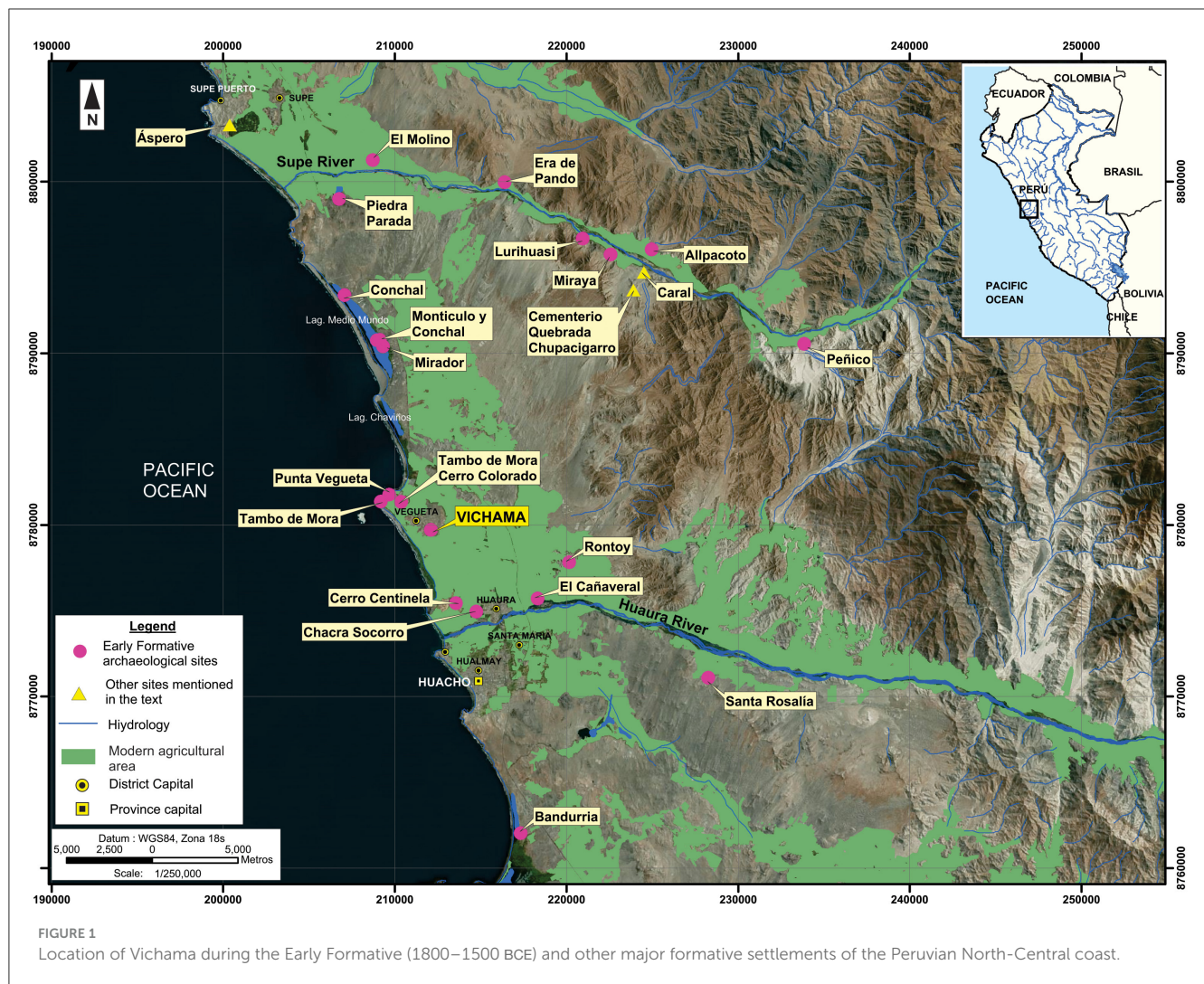
Studies suggest that a cold period along the Peruvian coast between 1800 and 1200 BCE produced a decrease in SSTs and an increase of marine productivity (Salvatteci et al., 2016, 2019), leading to changes in the equilibrium of political power to the benefit of coastal populations. High marine productivity of the Peruvian sea has been detected between ~1700 and 1500 BCE (Salvatteci et al., 2019), coinciding with the flourishing of several ceremonial centers along the coastal area such as Vichama (Shady et al., 2015) and Bandurria (Chu, 2011), located, respectively, along the coast of the northern and southern interbasins of Huaura Valley, the more productive of the PNCC. However, the extent to which changes in marine productivity may have led to an increased reliance on marine resources at the expense of agricultural products, well known in the region since previous periods, remains untested. To investigate this issue, we integrate stable isotope data ($\delta^{13}\text{C}_{\text{collagen}}$, $\delta^{15}\text{N}_{\text{collagen}}$, $\delta^{13}\text{C}_{\text{apatite}}$) and Bayesian stable isotope mixing models (BSIMMs) of human individuals from Vichama, an Early Formative (EF) coastal site with monumental architecture, “key” to understanding the timing of dietary changes and the nuances of the Formative economy. From a broader theoretical perspective, this article offers valuable insights into how climatic conditions influenced the rise and collapse of complex prehistoric societies (Kennett and Marwan, 2015).

Archaeological context: Vichama

Vichama is an archaeological site located in the modern city of Végueta, 130 km north of Lima, in the PNCC (UTM WGS84 N8779900/E212200). The site is at the right margin of the lower Huaura Valley (Huaura–Supe interbasin), at 1.5 km from the Pacific Ocean and 6.5 km northwest to the river mouth (Figure 1). The Huaura River is a permanent source of water that flows ~158 km from its origin in the Andean highlands (i.e., Sura Saca lagoon—Cordillera de Raura) to the sea and works as a natural corridor that links transversally the coast with important socioeconomic regions, such as the Mantaro basin and Eastern Andean lowlands (e.g., Alto Marañón, Alto Huallaga).

Although the lower Huaura Valley has been the object of archaeological prospections since the early 20th century (Engel, 1987; Tello, 2004), Vichama was not systematically studied until the 1970s (Aguilar, 2006; Cárdenas, 1977). Since 2007, Vichama has been intensively excavated and conserved by the Caral Project (Zona Arqueológica Caral-ZAC), sponsored by the Peruvian government and local institutions (Shady et al., 2008, 2015).

Archaeological evidence and radiocarbon dates indicate the site was occupied during two chrono-cultural periods: during the Early Formative–1 (EF-1, 1800–1500 BCE), when monumental architecture flourished through six architectonic periods (P1–P6), and during the Late Intermediate Period (LIP, 1000–1300 CE), when the site became a fishing village with decreased political



power in this section of the valley during a period of high marine productivity (Figure 2).

Vichama is a multicomponent complex that comprises nine sectors, including Formative monumental architecture (Vi-01) and shell middens (Vi-02, Vi-03), and architecture and cemeteries of later periods (Vi-04–Vi-09) scattered across 136 ha in the hills of Cerro Halconillo, a rocky elevation that rises 114 m above the sea level in the middle of one desertic oasis of 305 ha (Figure 3a).

During the EF-1, Vichama was part of an emerging complex polity in the lower Huaura Valley, which would have been composed of no <20 settlements with monumental architecture (Aguilar, 2006; Cárdenas, 1977). It is possible that Vichama represented the rise of a new sociopolitical center in the region following the decline of the Caral society. The nuclear area at that time comprised 29 buildings, including public (e.g., stepped platforms, sunken circular courts, squares, and walls with reliefs), and domestic architecture of orthogonal design spread across 25 ha (Shady et al., 2015). This area is divided into two halves, upper and lower, following the bipartite spatial division common in Andean settlements (Figure 3b). The ceremonial buildings exhibit various architectural features, including stone walls arranged in horizontal rows, architectural fills using mega-*shicras*, and walls adorned

with high-relief decorations (Shady et al., 2008, 2015). Changes in ceremonial architecture and paraphernalia (i.e., polychrome sculptures of unfired clay and particular iconography) suggest ideological transformations.

The diet in Vichama, current evidence

The “visual basin” of Vichama encompasses an approximate area of 9.2 km² that included diverse ecosystems that possibly were exploited for subsistence, among them, rocky and sandy beaches, swamps, *lomas* (fog oases), farming fields, the river, and the sea. The coast of Huaura Valley is one of the richest areas of the Peruvian sea, which currently cumulate ~20% of the total national production of fisheries (IMARPE, 2010, p. 64). Islands and islets (e.g., Anat, Azakan) located <1 km from the shore, potentially provided dense clam banks, marine turtles, and a variety of seabirds.

The importance of fishing is undeniable. The zooarchaeological record includes a total of 91 species (23 fish, 61 mollusks, 3 marine mammals, and 4 marine birds), recovered from primary contexts (see Supplementary material 1: S1—Marine species).

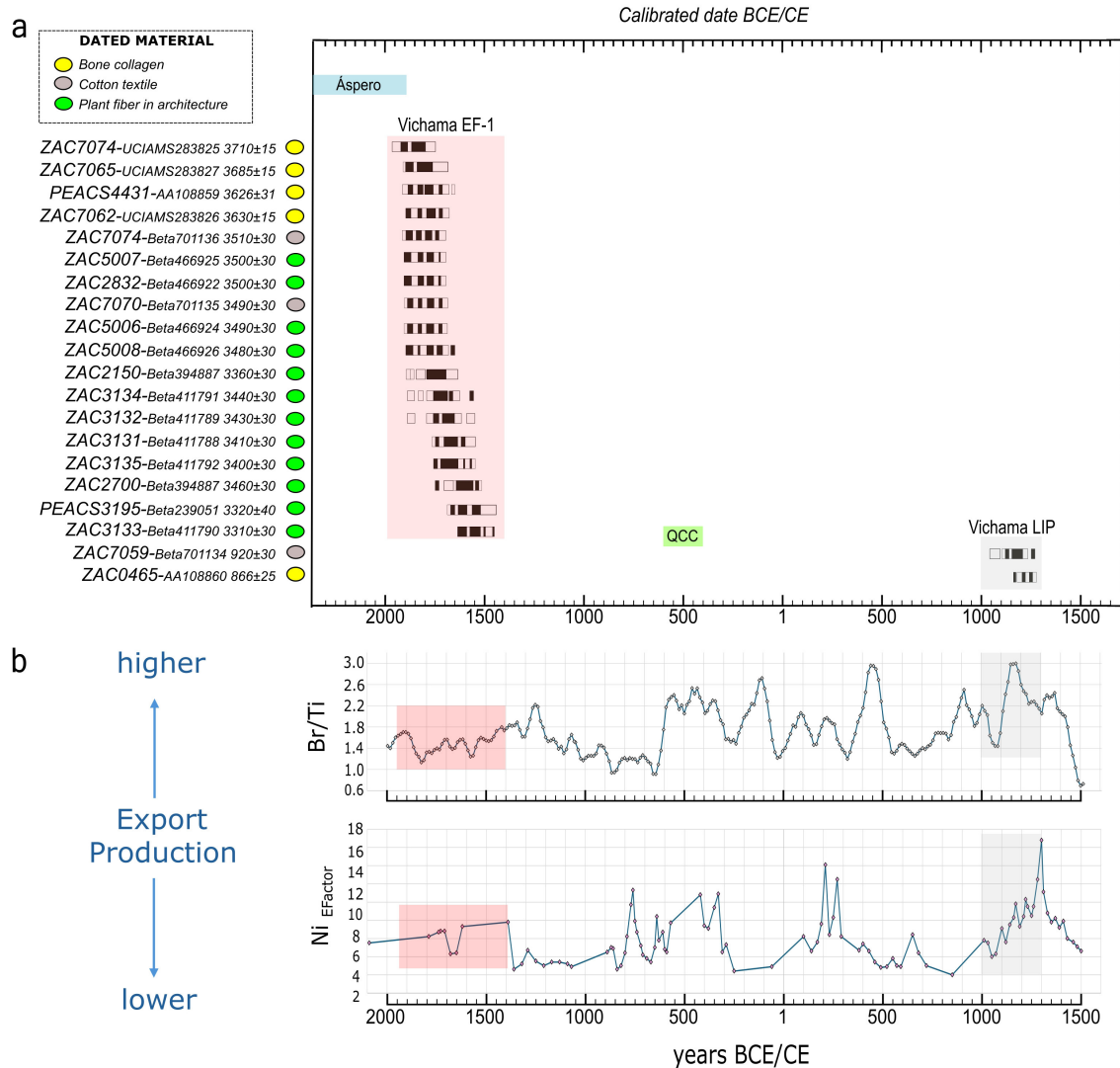


FIGURE 2

(a) Radiocarbon dates of Vichama and proxies for export productivity in the Peruvian coast during the Early Formative–1 (EF-1) and Late Intermediate (LIP) periods. See also the chronology of two sites mentioned in the article (i.e., Áspero and Quebrada Chupacigarro Cemetery–QCC). **(b)** Export productivity indexes: records of bromine-to-titanium ratio (Br/Ti, core M135-004-3, latitude 17°S) and authigenic nickel enrichment factor (EFactor; core G-10-GC-02, latitude 14°S). The bromine-to-titanium ratio is a semiquantitative method to estimate sedimentary total organic carbon, and the nickel (EFactor) indicates the organic sinking flux (Salvatteci et al., 2016). Colored areas represent the compared periods' classification (red for EF-1 and gray for LIP). Raw data available at: <https://doi.pangaea.de/10.1594/PANGAEA.887109>.

In addition, the exploitation of coastal salt-banks (i.e., Punta de Atahuanca and Salinas de Huacho, among others) to produce dry-salted fish probably was an important economic activity in the region during the Initial Formative and EF periods (Engel, 1987; Tello, 2004). Modern fishermen of Végueta employ several traditional techniques such as *redes de cerco*, diving, *chinchorro*, and *arte de pinta* that could be used in the past to capture the wide array of reported species (IMARPE, 2010, p. 67).

According to the last report (Yseki et al., 2024), the archaeobotanical inventory of edible plants in Vichama has yielded more than 35,000 macro-remains representing 17 taxa derived from 123 primary contexts (see [Supplementary material 1: S1—Edible plants species](#)). The botanical record includes fruits (guava, lucuma, pacay, avocado and *ciruela del fraile*), annuals like

chili peppers (e.g., *Capsicum baccatum*), beans (i.e., lima bean, common bean, and jack bean), squashes, and roots and tubers (i.e., achira, sweet potato, and potato). Based on their ubiquity, it seems that fruit trees, especially guava and lucuma, as well as chili peppers, were regularly consumed and used in ceremonial activities. Similarly, the high ubiquity in offering contexts of remains of lima bean, achira, sweet potato, and potato highlights the economic importance of these plants in Vichama (Yseki et al., 2024).

The absence of *Zea mays* (maize) macro-remains suggests that it was probably not grown, processed, or stored at Vichama. However, a recent study reported starch grains with potential fermentation-related damage in dental calculus of individuals from Áspero (Yseki et al., 2023), with a minimal presence of

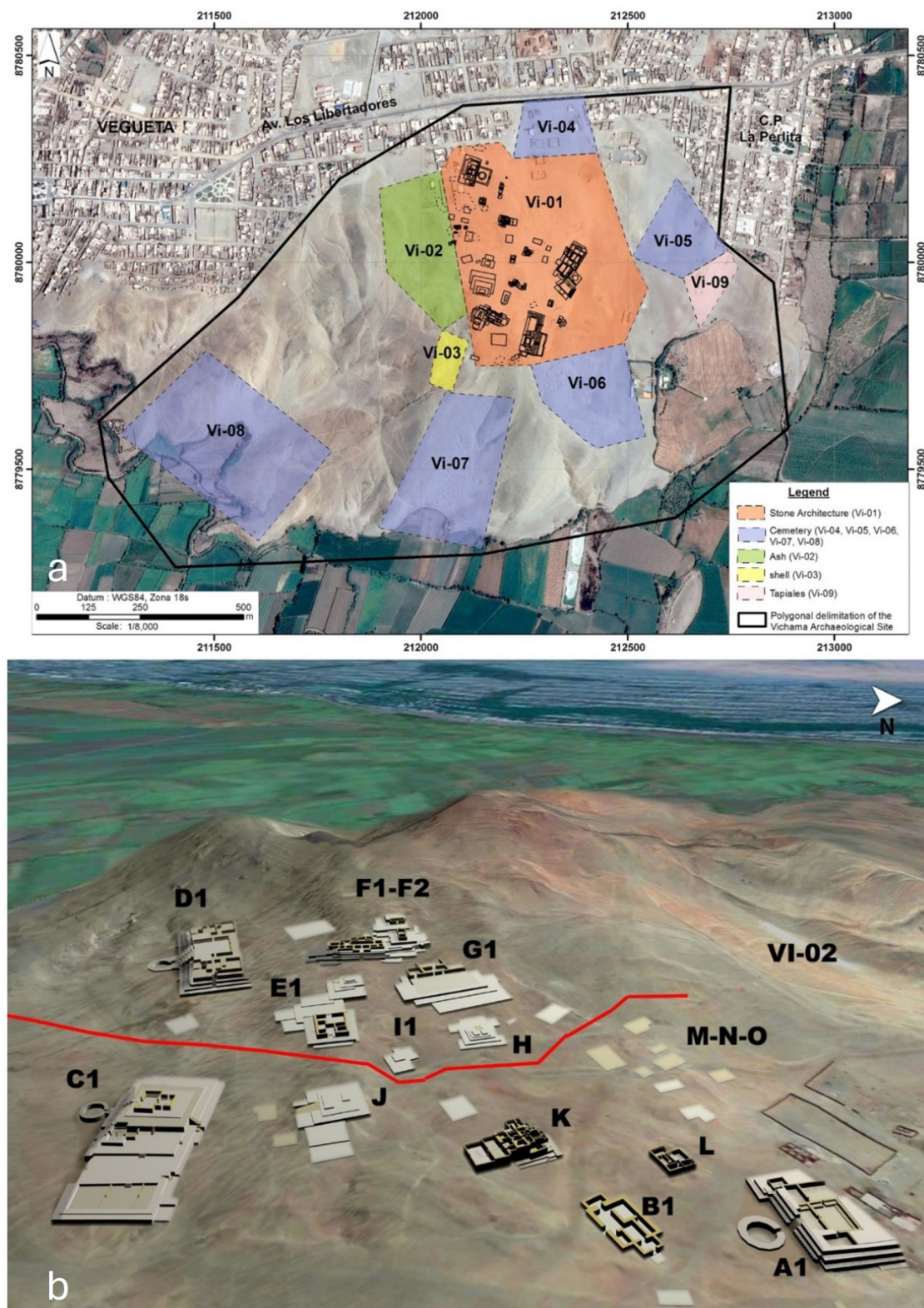


FIGURE 3

(a) Sectors of Vichama archaeological site. (b) Three-dimensional reconstruction of some relevant monumental buildings in the upper and lower halves of the site. Upper half: *Edificio Público Mayor* (Sector D1), *Edificio Las Ofrendas* (Sector F), *Edificio Público Residencial* (Sector E1), *Edificio Público G1*, *Edificio Público Mediano* (Sector H), *Edificio Público Menor* (Sector I1). Lower half: *Edificio Principal* (Sector A1), *Edificio Residencial de Elite* (Sector B1), *Edificio Público Los Depósitos* (Sector K), *Edificio de las Chakanas* (Sector C1), *Edificio Público Menor* (Sector L), *Edificio Residencial de Elite* (Sector J), *Sector Residencial* (Sector M-N-O), domestic and burial areas (VI-02). See [Supplementary material 2](#) for detailed locations of funerary contexts and individuals evaluated in this work.

maize macro-remains (Shady and Cáceda, 2008). Thus, maize consumption at Vichama cannot be ruled out based solely on macro-remains analysis, as maize may have been consumed as a beverage or flour (Yseki et al., 2024).

The marine fauna and some differences between periods suggest fluctuations in sea productive conditions linked to the upwelling of rich-nutrient marine waters. For instance, during the EF period (1800–1200 BCE), there is a general trend to increasing exported productivity, especially during the EF-1 (1800–1500 BCE), with some fluctuations (i.e., lower productivity between 1800 and 1600 BCE, with the lowest values around 1700 BCE and higher productivity between 1600 and 1500 BCE) that should have influenced dietary composition, possibly with higher consumption of marine products; however, the plant record shows that agriculture was ongoing during the flourishing of monumental architecture.

These conditions, however, could be relatively different from those observed during the LIP (1000–1300 CE) when productivity reached even higher values and enhanced upwelling conditions, with its maximum at ~1000–1100 CE (Kennett and Marwan, 2015). During the LIP, the archaeological deposits are plenty of marine remains, such as fish bones and shells, fishing nets, and artifacts for marine exploitation.

Stable isotopes in diet reconstruction

While faunal and plant remains can provide insight into shifts in economic practices, stable isotope analysis is more effective for targeting the net consumption of specific food resources at an individual level. Stable carbon and nitrogen isotope analyses of collagen ($\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$) and bioapatite ($\delta^{13}\text{C}_{\text{ap}}$) extracted from human bones and teeth offer valuable insights into the diets of ancient populations (Schoeninger and Reitsema, 2023). The $\delta^{13}\text{C}_{\text{coll}}$ is a proxy of protein sources and trophic position of consumers in the food web, as well as the photosynthetic pathway of the plants they consumed. The $\delta^{13}\text{C}_{\text{ap}}$ instead reflects the entire dietary carbohydrates, lipids, and proteins, providing a useful means to assess the energetic constituents of the diet and photosynthetic pathways (Jim et al., 2004; Kellner and Schoeninger, 2007). In the Andean central coast, C_3 plants, which use the Calvin–Benson photosynthetic pathway, are the most prevalent and typically exhibit mean $\delta^{13}\text{C}$ values of $-25.7 \pm 2.1\text{‰}$. In contrast, among C_4 , which follow the Hatch–Slack photosynthetic pathway, there are only two potentially edible domesticated plants (*kiwicha*—*Amarantus* sp., and maize—*Zea mays*), with typical values of approximately $-11.3 \pm 1.4\text{‰}$. Additionally, crassulacean acid metabolism (CAM) plants have isotopic values ($-10.8 \pm 0.2\text{‰}$) that overlap with those of C_4 (Pezo-Lanfranco and Colonese, 2024).

Usually, C_4 plant consumers show significantly higher $\delta^{13}\text{C}$ values (Kellner and Schoeninger, 2007). In coastal areas, however, using $\delta^{13}\text{C}$ to trace maize consumption can be challenging due to the presence of marine resources (i.e., fish and mollusks), which have overlapping $\delta^{13}\text{C}$ values to C_4 plants, approximately $-11.9 \pm 2.1\text{‰}$ (Pezo-Lanfranco and Colonese, 2024). In terms of $\delta^{15}\text{N}$ values, herbivores tend to have values 3–7‰ higher

than the plants they consume, while carnivores exhibit $\delta^{15}\text{N}$ values 3–5‰ higher than their prey. Because marine sources have higher isotopic values compared to terrestrial sources (Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984), marine fauna displays higher $\delta^{15}\text{N}$ values than terrestrial ones, linked to trophic fractionation within complex marine food webs (Chisholm et al., 1982; DeNiro and Epstein, 1981; Hedges and Reynard, 2007; Schoeninger, 2010; Schoeninger et al., 1983). Stable isotope analysis is particularly informative when combined with Bayesian mixing models for deriving quantitative estimates of dietary composition as probability distributions (Cheung and Szpak, 2021; Fernandes et al., 2014, 2015; Phillips, 2012).

Hypothesis and expectations

By employing a combination of stable isotope proxies from collagen ($\delta^{13}\text{C}_{\text{coll}}$, $\delta^{15}\text{N}_{\text{coll}}$, $n = 36$) and apatite ($\delta^{13}\text{C}_{\text{ap}}$, $n = 26$) of 38 human individuals from Vichama, and BSIMM estimations of the caloric contribution of the potential food sources (i.e., marine and terrestrial fauna, as well as C_3 and C_4 plants; Fernandes et al., 2014, 2015) consumed by 21 Vichama individuals (see Material and Methods for model implementation details), we aim to elucidate the primary sources of energy for two occupational periods at Vichama: EF-1 (1800–1500 BCE) and the LIP (1000–1300 CE).

We tested the hypothesis that changes in marine productivity influenced the degree to which marine resources were incorporated into Andean subsistence economies (Kennett and Marwan, 2015; Wilson et al., 2024). According to paleoclimatic data, an increased marine productivity between 1800 and 1500 BCE was concomitant with the flourishing of Vichama (Shady et al., 2015). However, the economic importance of plants and fish and their relative contribution to diet is unknown. It is expected that the inhabitants of Vichama, particularly during EF-1, relied more strongly on marine products as a significant part of their diet.

For comparison, the LIP (1000–1300 CE) was a time of climate cooling and decreasing SSTs, when marine productivity reached its peak (Kennett and Marwan, 2015). Because the LIP has been recognized as the period of higher development of agriculture in the Central Andes, under increasing conditions of upwelling and marine productivity, a mixed diet with a higher contribution of marine sources is expected. This reliance should be reflected in paleodietary reconstructions.

Results

Dietary reconstruction

The isotopic values of 38 human individuals from Vichama were classified into the two occupations, EF period (1800–1500 BCE, $n = 30$), and the LIP (1500–1300 CE, $n = 8$), used here for comparative purposes (Table 1, Supplementary material 1: S2 for individuals' contexts and bioarchaeological details and S3 for radiocarbon dates). Only a fraction of the 59 elements sampled (36 bones and 23 teeth) provided intact collagen with reliable $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$ values from bone ($n = 21$) or teeth ($n = 15$) according to accepted preservation criteria (DeNiro, 1985; Van Klinken,

TABLE 1 Isotopic values from Vichama individuals.

#	Period	ID	Sex	Age-range (years)	Tissue	Element (segment)	Age of tissue*	%C	%N	C:N	$\delta^{13}\text{C}_{\text{coll}}$	$\delta^{15}\text{N}$	$\delta^{13}\text{C}_{\text{ap}}$
1	EF-1 (P3)	ZAC 0458**	F	Adult	Bone	Rib	Adult	41.9	13.9	3.5	−16.9	13.4	−13.8
2	EF-1 (P3)	ZAC 0458	F	Adult	Tooth	LLPm (root)	5.5–14 yr	39.5	14.0	3.3	−17.8	11.8	−11.9
3	EF-1 (P3)	ZAC 7058	M	30–65 yr	Bone	Rib	30–65 yr	No collagen					−14.1
4	EF-1 (P4)	ZAC 7069**	M	22–32 yr	Bone	Rib	22–32 yr	42.8	15.1	3.3	−16.6	13	−13.2
5	EF-1 (P4)	ZAC 7069	M	22–32 yr	Tooth	1,8 (root)	8.0–16.5 yr	45.7	15.5	3.4	−18	11.6	n.a.
6	EF-1 (P4)	ZAC 7075	Und	4 yr ± 12 m	Bone	Rib	4 yr ± 12 m	No collagen					n.a.
7	EF-1 (P4)	ZAC 7075	Und	4 yr ± 12 m	Tooth	7,3 (root)	0.9–3.5 yr	No collagen					n.a.
8	EF-1 (P4)	ZAC 5905**	M	25–35 yr	Bone	Rib	25–35 yr	29.0	9.4	3.6	−17.5	14.3	−14.0
9	EF-1 (P4)	ZAC 5905	M	25–35 yr	Tooth	3,7 (root)	8–16.5 yr	44.8	16.1	3.3	−17.7	11.6	n.a.
10	EF-1 (P4)	PEACS 4431**	Und	2–5 yr	Bone	Rib	2–5 yr	42.7	13.7	3.3	−18	13.8	−14.6
11	EF-1 (P5)	ZAC 7056**	F	35–65 yr	Bone	Rib	35–65 yr	37.7	12.9	3.4	−16.3	15.6	−14.0
12	EF-1 (P5)	ZAC 7057**	Und	3 yr ± 12 m	Bone	Rib	3 yr ± 12 m	39.5	13.6	3.4	−14.1	18	−13.6
13	EF-1 (P5)	ZAC 7082	F	50–75 yr	Bone	Rib	50–75 yr	10.1	2.6	<u>4.5</u>	−20.5	16.6	n.a.
14	EF-1 (P5)	ZAC 7083	M	35–50 yr	Bone	Rib	35–50 yr	No collagen					n.a.
15	EF-1 (P5)	ZAC 7083	M	35–50 yr	Tooth	1,8 (root)	8.0–16.5 yr	No collagen					n.a.
16	EF-1 (P5)	ZAC 7085	F	7 yr ± 12 m	Bone	Rib	7 yr ± 12 m	No collagen					n.a.
17	EF-1 (P5)	ZAC 7085	F	7 yr ± 12 m	Tooth	1,1 (root)	4.5–11 yr	No collagen					n.a.
18	EF-1 (P5)	ZAC 1924	Und	12–16 yr	Bone	Rib	12–16 yr	17.8	6.4	3.2	−19.2	13.0	n.a.
19	EF-1 (P5)	ZAC 1924	Und	12–16 yr	Tooth	URPm (root)	6–14 yr	45.1	14.2	<u>3.7</u>	−15.8	17.9	n.a.
20	EF-1 (P6)	ZAC 7076**	M	16–19 yr	Bone	Rib	16–19 yr	18.0	5.9	3.6	−18.5	14.0	−14.5
21	EF-1 (P6)	ZAC 7076	M	16–19 yr	Tooth	M3 (root)	14.0–23.5 yr	43.5	15.3	3.3	−17.9	11.5	n.a.
22	EF-1	ZAC 7084	F	10 yr ± 30 m	Bone	Rib	10 yr ± 30 m	12.7	3.0	<u>5.0</u>	−20.9	14.6	n.a.
23	EF-1	ZAC 7084	F	10 yr ± 30 m	Tooth	3,3 (root)	5.5–14.5 yr	31.1	7.4	<u>4.9</u>	−17.6	17.2	n.a.
24	EF-1	ZAC 6645	F	30–65 yr	Bone	Rib	30–65 yr	No collagen					n.a.
25	EF-1	ZAC 7062**	M	35–65 yr	Bone	Rib	35–65 yr	41.9	14.9	3.3	−17.6	11.4	−11.3
26	EF-1	ZAC 7062	M	35–65 yr	Tooth	2,8 (root)	8.0–16.5 yr	42.0	14.5	3.4	−18.4	11.1	n.a.
27	EF-1	ZAC 7064	M	22–35 yr	Bone	Rib	22–35 yr	No collagen					−13.0
28	EF-1	ZAC 7064	M	22–35 yr	Tooth	4,2 (root)	4–8.5 yr	46.0	16.0	3.4	−19.4	8.2	n.a.
29	EF-1	ZAC 7065**	M	20–25 yr	Bone	Rib	20–25 yr	15.2	43.8	3.4	−16.0	13.9	−14.0

(Continued)

TABLE 1 (Continued)

#	Period	ID	Sex	Age-range (years)	Tissue	Element (segment)	Age of tissue*	%C	%N	C:N	$\delta^{13}\text{C}_{\text{coll}}$	$\delta^{15}\text{N}$	$\delta^{13}\text{C}_{\text{ap}}$
30	EF-1	ZAC 7065	M	20–25 yr	Tooth	4,1 (root)	4–8.5 yr	45.2	16.2	3.3	−18.2	12.1	n.a.
31	EF-1	ZAC 7066**	M	30–40 yr	Bone	Rib	30–40 yr	12.5	4.3	3.4	−20.3	12.0	−11.9
32	EF-1	ZAC 7067**	Und	8 yr $\pm$ 24 m	Bone	Rib	8 yr $\pm$ 24 m	42.7	14.9	3.3	−17.8	11.8	−12.8
33	EF-1	ZAC 7067	Und	8 yr $\pm$ 24 m	Tooth	3 fragm. (roots)	0.6–3.5 yr	46.5	14.2	<u>3.8</u>	−18.8	14.0	n.a.
34	EF-1	ZAC 7068**	F	25–40 yr	Bone	Rib	25–40 yr	42.4	14.7	3.4	−16.9	13.1	−11.8
35	EF-1	ZAC 7068	F	25–40 yr	Tooth	3,8 (root)	14.0–23.5 yr	45.7	15.5	3.4	−18.5	11.3	n.a.
36	EF-1	ZAC 7070**	F	20–30 yr	Bone	Rib	20–30 yr	42.2	14.5	3.4	−14.6	12.9	−11.5
37	EF-1	ZAC 7071**	M	25–55 yr	Bone	Rib	25–55 yr	43.2	15.1	3.3	−14.9	12.1	−11.2
38	EF-1	ZAC 7071	M	25–55 yr	Tooth	Pm (root)	5.5–15 yr	75.3	25.2	3.5	−15.0	11.6	n.a.
39	EF-1	ZAC 7072	Und	2 yr $\pm$ 8 m	Bone	Rib	2 yr $\pm$ 8 m	17.1	5.0	<u>4.0</u>	−19.7	15.1	n.a.
40	EF-1	ZAC 7073	Und	6 yr $\pm$ 24 m	Bone	Rib	6 yr $\pm$ 24 m	No collagen					n.a.
41	EF-1	ZAC 7073	Und	6 yr $\pm$ 24 m	Tooth	7,3 (root)	0.9–3.5 yr	No collagen					n.a.
42	EF-1	ZAC 7074**	M	30–40 yr	Bone	Rib	30–40 yr	42.1	14.5	3.4	−17	13.0	−14.2
43	EF-1	ZAC 7074	M	30–40 yr	Tooth	1,8 (root)	8.0–16.6	40.2	14.2	3.3	−17.2	13.6	n.a.
44	EF-1	ZAC 7077**	M	40–60 yr	Bone	Rib	40–60 yr	42.3	14.9	3.3	−17.5	11.8	−12.7
45	EF-1	ZAC 7080	F	20–25 yr	Bone	Rib	20–25 yr	No collagen					−13.9
46	EF-1	ZAC 7080	F	20–25 yr	Tooth	1,8 (root)	8.0–16.5 yr	44.4	16.2	3.2	−17.4	11.8	n.a.
47	EF-1	ZAC 7081	Und	6 m $\pm$ 3 m	Bone	Rib	6 m $\pm$ 3 m	19.6	4.8	<u>4.8</u>	−18.7	27.5	n.a.
48	EF-1	ZAC 0955	M	50–70 yr	Bone	Rib	50–70 yr	No collagen					−12.1
49	LIP	ZAC 7054**	Und	7 yr $\pm$ 24 m	Bone	Rib	7 yr $\pm$ 24 m	37.5	13.4	3.3	−17.9	11.5	−13.9
50	LIP	ZAC 7054	Und	7 yr $\pm$ 24 m	Tooth	1,6 (root)	3.5–7 yr	47.7	15.9	3.5	−17.8	12.4	n.a.
51	LIP	ZAC 7055	F	30–40 yr	Tooth	4,5 (root)	6.5–12.0 yr	44.6	15.3	3.4	−16.7	15.6	n.a.
52	LIP	ZAC 7059**	M	15–19 yr	Bone	Rib	15–19 yr	44.3	15.6	3.3	−12.3	16.4	−7.7
53	LIP	ZAC 7060	M	45–55 yr	Bone	Rib	45–55 yr	16.4	4.6	<u>4.2</u>	−20.2	13	n.a.
54	LIP	ZAC 7060	M	45–55 yr	Tooth	3,8 (root)	14.0–23.5 yr	44.0	15.9	3.2	−18.1	12.1	n.a.
55	LIP	ZAC 7061**	M	20–25 yr	Bone	Rib	20–25 yr	41.4	15.0	3.2	−11.0	13.7	−6.8
56	LIP	ZAC 7078	M	50–70 yr	Bone	Rib	50–70 yr	24.8	7.7	<u>3.8</u>	−17.7	12.8	n.a.
57	LIP	ZAC 7079	M	25–50 yr	Bone	Rib	25–50 yr	No collagen					n.a.
58	LIP	ZAC 7079**	M	25–50 yr	Tooth	4,3 (root)	5.5–14.5 yr	43.6	15.4	3.3	−15.2	17.4	−10.4
59	LIP	ZAC 0465**	F	35–40 yr	Tooth	3,5 (root)	6.5–12.0 yr	45.0	14.4	3.6	−16.9	13.4	−11.9

EF-1, Early Formative–1 (1800–1500 BCE); LIP, Late Intermediate Period (1000–1300 CE); P, architectural period; M, male; F, female; Und, undetermined; Adult, adult individual without age-range estimation; n.a., value not available. Individuals with underlined C:N ratios were eliminated from analyses.

*The age range of the tissue used in the analysis (e.g., teeth develop at infant or child ages, so the isotopic values correspond to early life). Recognized teeth are reported in FDA nomenclature; unrecognized teeth are reported in anthropological nomenclature.

**Individuals included in Bayesian stable isotope mixing model analysis.

1999). Attenuated total reflectance–Fourier transform infrared spectroscopy (ATR-FTIR) studies conducted in a subsample of 10 individuals consistently suggest that no diagenetic alteration affected the inorganic fraction of bones from Vichama contexts (France et al., 2020; see [Supplementary material 1: S4](#) for the ATR-FTIR data). Thus, $\delta^{13}\text{C}_{\text{ap}}$ values ($n = 26$) were included in our analysis to complement the paleodietary information.

The $\delta^{13}\text{C}_{\text{coll}}$ values from both bone and tooth dentin ranged from -20.3 to -11.0 ‰, $\delta^{15}\text{N}$ values ranged from $+8.2$ to $+18.0$ ‰, whereas $\delta^{13}\text{C}_{\text{ap}}$ values ranged from -14.6 to -6.8 ‰ ([Supplementary material 1: S5](#)).

Although the contribution of marine protein is evident in some male individuals ([Figure 4a](#)), the mean $\delta^{15}\text{N}$ values are lower than expected for fishers and suggest the consumption of marine protein of a low trophic level, possibly little fishes and shellfish (with mean values of $\delta^{13}\text{C}_{\text{coll}} = -12.3$ ‰, $\sigma = 0.5$, and $\delta^{15}\text{N} = +10.4$ ‰, $\sigma = 1.2$) over the entire sequence. No significant differences were observed for $\delta^{13}\text{C}_{\text{coll}}$, $\delta^{15}\text{N}$, and $\delta^{13}\text{C}_{\text{ap}}$ values between females and males or between preadults and adults for both EF-1 and LIP occupations ([Supplementary material 1: S5](#)). The significant difference observed between adults and preadults of EF-1 probably resulted from the weaning effect in a couple of infants (i.e., PEACS4431 and ZAC7057) or different protein sources (i.e., ZAC7067) in some preadults.

Inter-population comparisons revealed a significant difference only for $\delta^{13}\text{C}_{\text{ap}}$ (Mann–Whitney $U = 18.50$, $p = 0.027$). In general, the $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{13}\text{C}_{\text{ap}}$ indicate diets dominated by protein and energy sources from C_3 ecosystems ([Figure 4b](#); [Kellner and Schoeninger, 2007](#)). Nevertheless, individuals from the LIP exhibited a much broader range of $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$ values, indicating relatively higher marine protein consumption, notably by some male individuals (e.g., ZAC7061, ZAC7059), compared to the EF-1 population.

The comparisons of protein sources of Vichama EF-1 and LIP phases with other populations from the PNCC show a trend to consume a diet intermediary between that of Áspero, the most representative site of fishermen in the Supe Valley during the Initial Formative (3000–1800 BCE), based on C_3 plants and marine protein of higher trophic level, and the diet of later farmers from Quebrada Chupacigarro cemetery (middle Supe Valley, Late Formative, 500–400 BCE), virtually based on plants ([Pezo-Lanfranco et al., 2022](#)). LIP diets show an overlap area greater than EF-1 with Áspero diets ([Figure 5](#)).

In addition, we estimate the proportions of dietary components estimated with BSIMMs for 21 Vichama individuals with a set of complete isotopic data ([Table 2](#), [Figure 6](#); see also [Supplementary material 1: S6](#) for the model's results). These results suggest that most calories consumed came from C_3 plants (contribution ranging from 14% to 86%), followed by fish and mollusks (8% and 58%), C_4 plants (3%–19%), and terrestrial fauna (3%–11%).

Thus, most individuals from the EF-1 occupation of Vichama show values compatible with a wide farming–fishing diet, with an unexpectedly high contribution of plants to people living near the sea. The comparison of diets between EF-1 and the LIP suggests a trend of increasing marine protein consumption in the later period, fewer C_3 plants, and a discrete increase of C_4 and terrestrial

protein. The Kullback–Leibler divergence is 0.141, indicating a moderate difference in the average probability distributions among individuals of EF-1 and LIP, consistent with dietary change between periods with some overlap.

Discussion

The nature of diet at Vichama

Our study suggests that the two distinct occupational phases of Vichama were underpinned by different economic systems. During EF-1, dated to 1800–1500 BCE, although some individuals relied significantly on marine resources for calories (>25%), subsistence was based primarily on the cultivation of C_3 plants. Plant remains, including several high-energy crops like tubers, beans, and fruits, were found mainly in funerary contexts associated with public buildings, yet our results reveal the significance of these plants at the household level beyond ritual use.

This agricultural production has likely supported Vichama's political prominence at the end of the Caral era. Cultivation seems to have been a plausible activity in Vichama during the EF-1. The agricultural area near Vichama extends approximately 970 ha, and the water sources are located <2 km from Vichama. In the zone, the phreatic level is approximately 0.85 m depth ([INRENA, 2005](#)).

Evidence of botanical macro- and micro-remains shows the consumption of several domesticated crops in coastal settlements during the Initial Formative (3000–1800 BCE; [Haas et al., 2013](#); [Shady, 2006a,b,c](#); [Vega-Centeno, 2005](#); [Yseki et al., 2023, 2024](#); [Zechenter, 1988](#)). For example, plant micro-remains from human dental calculus at Áspero, in the same region, indicate significant sweet potato and moderate potato consumption during the Initial Formative period ([Yseki et al., 2023](#)), despite their scarcity in the macro-botanical record ([Shady and Cáceda, 2008](#)).

Vichama's location is appropriate for maize cultivation due to extensive arable lands and water availability. Interestingly, the isotopic evidence obtained by this work suggests a marginal contribution of C_4 (lower than 10% in most cases) during EF-1 and agrees with the lack of maize evidence in the archaeological record. The near absence of maize in Vichama contrasts with its presence in some early sites from adjacent valleys of the PNCC ([Haas et al., 2013](#); [Shady, 2006b](#); [Vega-Centeno, 2005](#); [Zechenter, 1988](#)). In Áspero, maize starch has been detected in dental calculus ([Yseki et al., 2023](#)), and in Pativilca Valley, maize pollen and starches appear as early as 2500 cal BCE ([Haas et al., 2013](#)). The presence of amaranth could account for the C_4 signal detected at Vichama, although no macro-remains of this plant have been recorded at the site, unlike at Caral, located 30 km to the northeast, where amaranth has been documented in an earlier period ([Shady, 2006c](#)).

Approximately 3,000 years later, during the LIP (1300–1500 CE), when Vichama had long lost its regional political influence, the site's residents relied primarily on C_3 plants, supplemented with a greater intake of marine resources. This increased focus on marine organisms is corroborated by the presence of fishing gear, such as nets and fishhooks made from mussel shells, as well as abundant

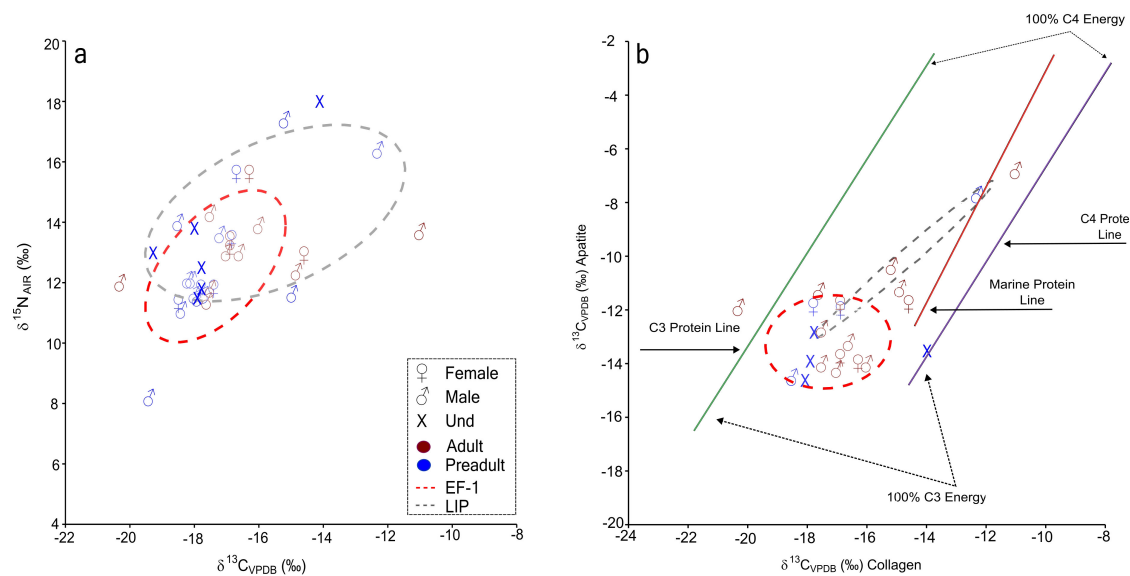


FIGURE 4

Scatterplot of stable isotope markers in Vichama individuals of Early Formative period and the Late Intermediate Period and overlapping standard ellipse areas (estimated for 68.5% of the population), for comparison. (a) $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$ values. (b) $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{13}\text{C}_{\text{ap}}$ values in the workspace of Kellner and Schoeninger (2007). V-PDB, Vienna Pee Dee Belemnite; AIR, atmospheric air.

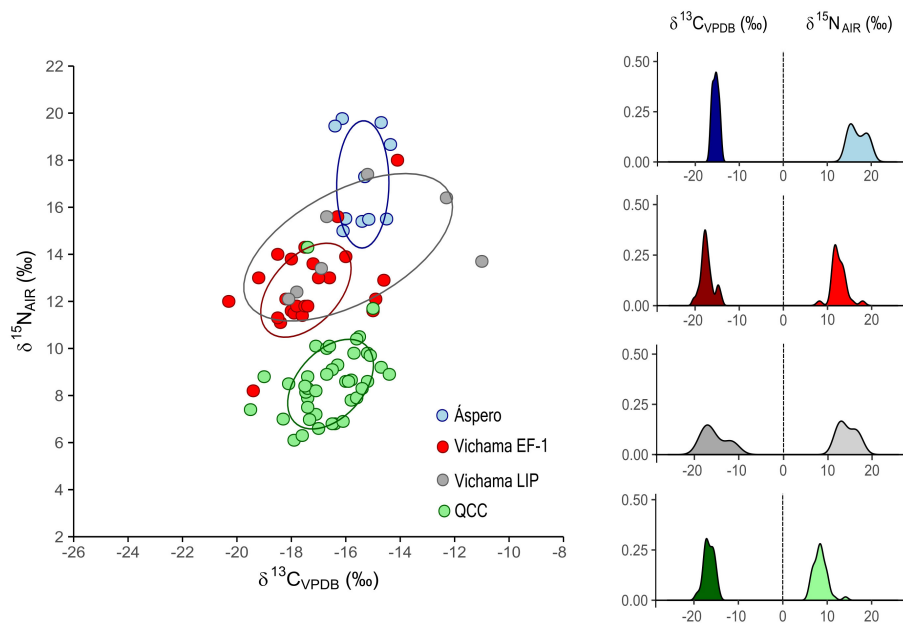


FIGURE 5

Scatterplot of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ with standard ellipse areas (estimated for 68.5% of the population), and density kernel plots of $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$ values of Vichama and other Formative populations from the Peruvian North-Central coast. EF-1, Early Formative-1 period; LIP, Late Intermediate Period; QCC, Quebrada Chupacigarro Cemetery.

fish and shell remains, all attesting to extensive fishing activities during the LIP. While maize may have been more consumed during the LIP, isotopic equifinality complicates distinguishing between C_4 plants and marine carbon sources. Two young male individuals from the LIP (ZAC7059 and ZAC7061) exhibit values of C_4 intake of approximately 20%; however, both consumed

approximately 40%–60% of calories from marine sources and show auditory exostoses, an osteological marker associated with repetitive aquatic activity in cold waters (Pezo-Lanfranco et al., 2009), suggesting that they were divers or fishers rather than maize consumers. In contrast, the only individual from EF-1 with auditory exostosis (ZAC5905, a male) shows, counterintuitively,

TABLE 2 Estimates of dietary carbon/calories contribution of each food group in Vichama individuals.*

Period	ID	Sex	Age range (years)	C ₄ plants		C ₃ plants		Terrestrial protein		Marine protein	
				$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
EF-1	ZAC 0458	F	Adult	0.05	0.03	0.74	0.08	0.06	0.05	0.15	0.05
EF-1	ZAC 7069	M	22–32 yr	0.05	0.03	0.74	0.09	0.06	0.05	0.14	0.06
EF-1	ZAC 5905	M	25–35 yr	0.04	0.03	0.78	0.07	0.06	0.04	0.12	0.05
EF-1	PEACS 4431	Und	Preadult	0.04	0.03	0.78	0.07	0.06	0.04	0.12	0.05
EF-1	ZAC 7056	F	35–65 yr	0.05	0.04	0.70	0.09	0.08	0.05	0.17	0.06
EF-1	ZAC 7057	Und	3 yr ± 12 m	0.07	0.05	0.56	0.10	0.11	0.07	0.26	0.08
EF-1	ZAC 7076	M	16–19 yr	0.03	0.02	0.81	0.07	0.05	0.03	0.11	0.04
EF-1	ZAC 7062	M	35–65 yr	0.06	0.04	0.76	0.09	0.05	0.04	0.14	0.06
EF-1	ZAC 7065	M	20–25 yr	0.05	0.04	0.71	0.08	0.07	0.05	0.17	0.06
EF-1	ZAC 7066	M	30–40 yr	0.03	0.02	0.86	0.05	0.03	0.02	0.08	0.03
EF-1	ZAC 7067	Und	8 yr ± 24 m	0.05	0.04	0.79	0.08	0.04	0.03	0.12	0.05
EF-1	ZAC 7068	F	25–40 yr	0.07	0.05	0.66	0.09	0.08	0.05	0.19	0.06
EF-1	ZAC 7070	F	20–30 yr	0.08	0.05	0.53	0.11	0.11	0.08	0.28	0.08
EF-1	ZAC 7071	M	25–55 yr	0.08	0.06	0.58	0.11	0.10	0.07	0.24	0.08
EF-1	ZAC 7074	M	30–40 yr	0.05	0.04	0.73	0.08	0.06	0.04	0.15	0.06
EF-1	ZAC 7077	M	40–60 yr	0.05	0.03	0.77	0.09	0.05	0.04	0.12	0.05
LIP	ZAC 7054	Und	7 yr ± 24 m	0.04	0.03	0.81	0.07	0.04	0.03	0.11	0.05
LIP	ZAC 7059	M	15–19 yr	0.17	0.09	0.20	0.12	0.20	0.11	0.43	0.11
LIP	ZAC 7061	M	20–25 yr	0.19	0.10	0.14	0.09	0.16	0.10	0.58	0.14
LIP	ZAC 7079	M	25–50 yr	0.08	0.05	0.50	0.12	0.14	0.08	0.28	0.08
LIP	ZAC 0465	F	35–45 yr	0.07	0.04	0.67	0.09	0.08	0.06	0.18	0.06

EF-1, Early Formative–1 (1800–1500 BCE); LIP, Late Intermediate Period (1000–1300 CE); P, architectural period; M, male; F, female; Und, undetermined.
*Estimates based on FRUITS v. 2.1.1 only for individuals with $\delta^{13}\text{C}_{\text{coll}}$, $\delta^{15}\text{N}_{\text{coll}}$ and $\delta^{13}\text{C}_{\text{ap}}$ values. Foods (%): estimates of dietary carbon/calories contribution of each food group, expressed as relative contributions (adding to 100%) with an associated 1 σ uncertainty (Fernandes et al., 2015, Table 5).

an unexpected low proportion of marine contribution to diet and $\delta^{15}\text{N}$ values compatible with marine resources from the lower trophic level.

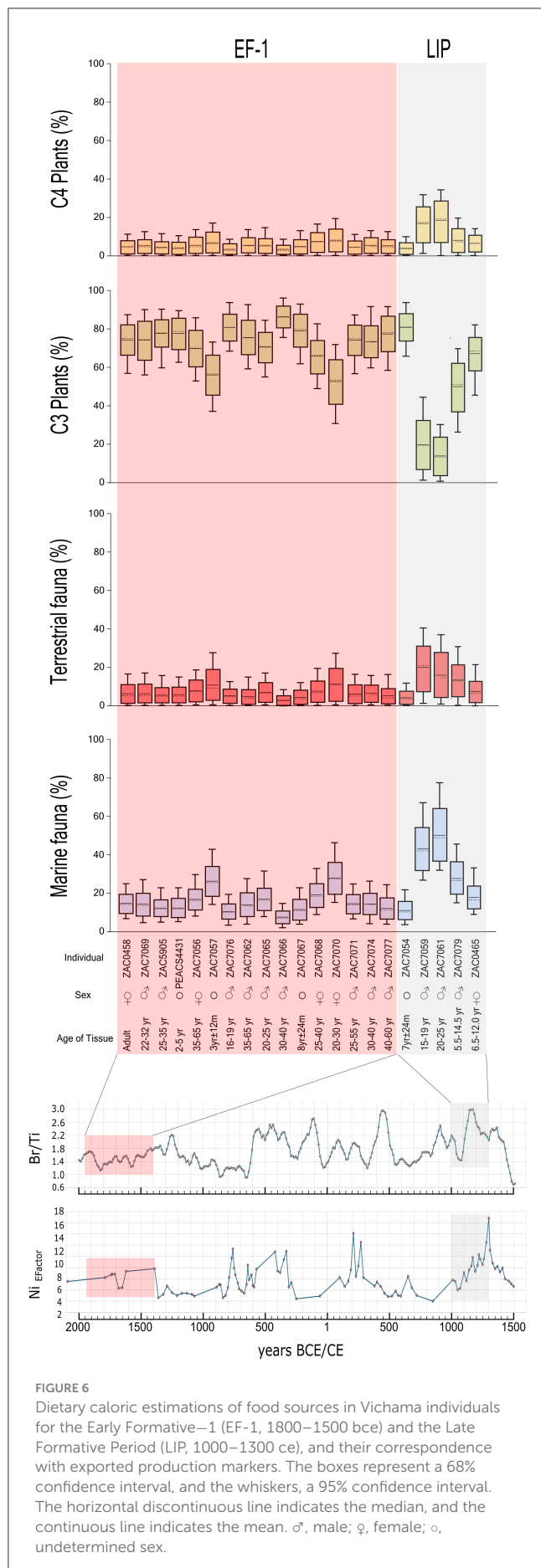
The overlap between maize and marine carbon values remains a potential source of uncertainty in isotopic analyses for this region. Regardless, if maize was consumed in Vichama during either EF-1 or the LIP, it likely did not constitute a staple or significant dietary component, contributing <30% of total dietary calories (Ambrose and Norr, 1993).

During the EF-1, terrestrial mammal consumption appears to have been occasional, with contributions from these protein sources increasing in the LIP (20% of total calories), likely due to a greater availability of camelids during this period (León, 2013). The faunal record at Vichama includes only six taxa: three bird species, commensal rodents, frogs, and camelids, the latter being the only potentially edible domesticated taxon. However, archaeozoological studies of inter-period consumption are still pending. The limited availability of domesticated species in the Andes, such as camelids, guinea pigs, and dogs, along with certain wild species from the *lomas* and desert areas, however, suggests that terrestrial protein remained a relatively minor dietary component during the Formative period, as observed in other studies

(Pezo-Lanfranco et al., 2022; Pezo-Lanfranco and Colonese, 2024). As a potential limitation of this study, the presence of little fish species can lead to mimicking the signal of wild terrestrial protein from *lomas*, potentially C₄ protein (Coutts et al., 2011; Cadwallader et al., 2012).

Although the archaeological record of EP-1 and the LIP support fishing activities for both periods, our results revealed that the reliance on marine products was higher during the LIP, which coincides with a time of high marine productivity, compared to EP-1. However, due to the limited LIP sample size, these interpretations should be considered provisional pending further evidence.

Finally, although some preadult individuals included in the BSIMMs could theoretically retain nitrogen isotopic signals from breastfeeding and weaning, leading to spurious interpretations, this is unlikely, as the analyzed tissues (tooth roots) correspond to older children, who typically consume an adult diet. Among the LIP individuals, two are adults and three are children or preadolescents, with sampled tissues ranging from 5.5 to 14.5 years. Previous research on weaning patterns in Andean populations places the completion of weaning between 1.5 and 3 years of age (see Pezo-Lanfranco et al., 2020 for a comprehensive review), suggesting that the isotopic values in the LIP are not influenced by the weaning



process. In the case of EF-1, among two analyzed infants (PEACS 4431 and ZAC7057), only ZAC7057 shows an elevated nitrogen value, which likely indicates ongoing breastmilk consumption and could potentially mimic a high intake of marine protein in the model. All other individuals analyzed are adults.

Dietary evidence and climate oscillations in Vichama

The isotope data generated in this study suggests two distinct economic regimes that are likely mirroring changes in political organization at Vichama over time. Food production systems during the EF-1 period were likely coordinated by centralized political institutions, aimed at generating surplus through intensified agriculture. By contrast, the diversified diet observed during the LIP period reflects the absence of these centralized systems at Vichama. This shift supports the existence of a diversified economy focused on small-scale farming and fishing for household consumption, with a reduced emphasis on surplus generation. These economic systems may also have been shaped by climate oscillations and the prevailing ecological conditions.

Wet and dry alternances that fueled and inhibited marine productivity, fishing activity, and, possibly, the expansion and contraction of *lomas* and farming fields into the region. These phenomena are linked to complex ocean-atmosphere interactions (Salvatteci et al., 2019), including oscillations in the Southern Pacific Anticyclone, trade winds, and coastal winds with effects on marine currents (Salvatteci et al., 2016, 2019; Yseki et al., 2022).

Apart from dietary adaptation, those fluctuating climate conditions could also be reflected in sociopolitical resilience and ideological response to environmental constraints, as suggested by the presence of climate-linked deities in Vichama's iconography (e.g., frog-human deity), potentially reflecting ideological adaptations to environmental constraints (Shady et al., 2015).

Reliance on marine protein during the EF-1 period might have been limited by lower biomass and marine productivity along the Peruvian coast at that time. Between 2300 and 1300 BCE, SSTs showed reduced seasonality, with cooler summers compared to present conditions (Carré et al., 2014; Loubere et al., 2013). Additionally, multidecadal fluctuations in upwelling and sea surface temperature between 1800 and 1500 BCE suggest that the EF-1 period at Vichama unfolded amid highly variable oceanographic conditions (Salvatteci et al., 2016, 2019), potentially making marine resources less predictable. Interestingly, this period corresponds to a greater reliance on C₃ plants.

As argued by previous research (Caramanica et al., 2020; Contreras, 2010; Dillehay and Kolata, 2004; Lima et al., 2023; Wilson et al., 2024), these oscillations coupled with ENSO alternances, could have been produced an opportunistic intensification of certain products (fisheries/crops) when technological level, and sociopolitical conditions allow it, producing corresponding diets with verifiable marine-farming fluctuations over the time. Theoretically, under El Niño-like conditions, the concurrence of drops in marine productivity with wetter conditions (raining) along the coast and *lomas* flourishing, despite landslides and disasters, would lead to increased land productivity in a sort of "high-risk farming". By comparison, under

La Niña-like conditions, sea temperatures cooling, increased upwelling, and marine productivity, concomitant to a dry climate (i.e., lower rainfall and *lomas* contraction), would have fueled a “low-risk farming” and greater marine production, probably with more marine fauna and more maize in the record, as we can observe during the LIP.

Climate conditions during EF-1 (1800–1500 BCE) at Vichama also included relatively wet periods in the highlands and dry conditions in the coastal valleys, marked by greater seasonality in river flows, with increased precipitation in the wet season and lower runoff during the dry season (Leclerc, 2023; Salvattecchi et al., 2019). The development of irrigation systems could have enabled intensified agriculture during the wet season, allowing surplus production to sustain populations through the drier months. Conversely, during the LIP, cooling sea temperatures, enhanced upwelling, and increased marine productivity, coupled with drier climates marked by reduced rainfall and contraction of *lomas* vegetation, may have fostered a shift toward greater reliance on marine resource exploitation alongside small-scale farming (Carré et al., 2014; Leclerc, 2023; Loubere et al., 2013; Salvattecchi et al., 2019).

This study offers new insights into how climate variability shaped subsistence economies in early Andean societies and expands our understanding of the trajectory of Andean civilization. In this sense, our assessment of subsistence patterns during EF-1, a period of emerging political complexity, aligns well with the idea that decreased marine productivity may have encouraged greater reliance on, and intensification of, terrestrial resources (Wilson et al., 2024). Conversely, our findings partially support the hypothesis that stable climatic conditions favor the development of agrarian societies, whereas climatic volatility contributes to political instability, decentralization, and fragmentation (Kennett and Marwan, 2015). Opportunism in the exploitation of available resources and resilience in the face of climatic challenges appear to have been key behaviors of these societies. Climate oscillations could have represented a challenging opportunity to develop adaptive buffer strategies, such as the intensification of farming or other economic activities. This may coincide with the hegemony of coastal, inland, or highland societies over different periods.

These results should be refined and tested by future research taking into consideration some limitations: (1) palaeoceanographic and climate data are fragmentary, ambiguous, and subject of interpretation and do not necessarily can be congruent with our conclusions and (2) equifinality, that is, varying combinations of food contributions that may produce the same isotopic values in a consumer, persists as a potential issue for interpretations.

Materials and methods

Individuals and samples

This is a multiproxy stable isotope study designed to reconstruct the composition of Vichama diet in quantitative terms. Our aim is to investigate the economy of Vichama to unravel the role of marine and vegetal resources in the processes of social complexity during the EF period.

A total of 59 samples (36 bones and 23 teeth) from 38 human individuals recovered from burial contexts of Vichama were sampled for the analysis. The skeletal elements recovered for isotope analyses were mainly ribs and long bones, carpals, or cranial bones when ribs were not available. Teeth were sampled when available, and isotopic values were obtained from roots, which makes a valid direct comparison of tooth and bone samples.

Individuals' sex and age were estimated using standardized methods (Buikstra and Ubelaker, 1994). To control the potential confusing factors of breastfeeding and weaning diets, for comparisons, individuals were classified in two categories (i.e., preadults and adults) according to the tissues (i.e., teeth or bones) that originate the values (AlQahtani et al., 2010).

Radiocarbon dates

The chronological framework of this work is based on 8 direct [Accelerator Mass Spectrometry (AMS) radiocarbon dates from individuals' collagen, and fabrics from funerary contexts], and 12 indirect radiocarbon dates from associated material or stratigraphy (R. Shady personal communication, June 2024). Radiocarbon dates of Vichama come from the AMS facilities of three different laboratories using in-house protocols through commercial services. Individuals' dates were calibrated (bce/ce) with Calib 8.1.0 package (Stuiver and Reimer, 1993), using the Mixed Marine SoHCal 20 calibration curve (Heaton et al., 2020; Hogg et al., 2020), a local marine radiocarbon reservoir correction value ($\Delta R = 200 \pm 20$) estimated from paired samples (i.e., bone collagen and cotton fabrics) of the burial context ZAC7074. For individuals directly dated, we included the mean relative contribution of marine carbon to collagen calculated using Food Reconstruction Using Isotopic Transferred Signals (FRUITS) for each phase. Calibrated dates were rounded to 10 (see [Supplementary material 1: S3](#)). Individuals who were not directly dated were assigned to each period according to archaeological methods (i.e., stratigraphy, funerary patterns, pottery styles, and textiles' decorations).

Laboratory procedures

First, samples were cleaned mechanically to remove surface contaminants. Then, samples were divided for collagen and apatite extractions. Collagen was extracted in the Institut de Ciència i Tecnologia Ambientals of the Universitat Autònoma de Barcelona (Spain).

Samples were physically cleaned and immersed in 0.6 M HCl at 4°C for several days, for demineralization, then rinsed with ultrapure water and immersed in 0.05 M sodium hydroxide (NaOH) for 20 min at room temperature. The NaOH wash cycles were repeated as needed, typically 1 or 2 times, until no further color change occurred in the solution. Samples were rinsed three times with ultrapure water for 10 min each to ensure the complete removal of NaOH. Samples were gelatinized in 0.001 M HCl (pH3) at 80°C for 48 h. The supernatant containing collagen was filtered using polyethylene Eze filters (9 mL, pore size 60–90 µm, Elkay Laboratories Ltd.), then frozen for at least 48 h at

–20°C, and freeze-dried. Stable isotope analysis of successfully extracted samples was performed at SUERC, East Kilbride (UK) using a Delta V Advantage continuous-flow isotope ratio mass spectrometer coupled via a ConFloIV to an IsoLink elemental analyzer (Thermo Scientific, Bremen, Germany). Bone collagen (approximately 0.7 mg) was combusted in the presence of oxygen in a single reactor containing tungstic oxide and copper wires at 1,020°C to produce nitrogen (N₂) and carbon dioxide (CO₂). A magnesium perchlorate trap was used to eliminate water produced during the combustion process, and the gases were separated in a Gas chromatography (GC) column heated between 70°C and 240°C. Helium was used as a carrier gas throughout the procedure. N₂ and CO₂ entered the mass spectrometer via an open split arrangement within the ConFloIV and were analyzed against their corresponding reference gases. The International Atomic Energy Agency reference materials USGS40 (L-glutamic acid, $\delta^{13}\text{C}$ Vienna Pee Dee Belemnite (V-PDB) = $-26.39 \pm 0.04\text{‰}$, $\delta^{15}\text{N}$ (AIR) = $-4.52 \pm 0.06\text{‰}$) and USGS41a (L-glutamic acid, $\delta^{13}\text{C}$ (V-PDB) = $36.55 \pm 0.08\text{‰}$, $\delta^{15}\text{N}$ (AIR) = $47.55 \pm 0.15\text{‰}$) were used to normalize $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values. Normalization was checked using the well-characterized Elemental Microanalysis IRMS fish gelatin standard B2215 ($\delta^{13}\text{C}$ (V-PDB) = $-22.92 \pm 0.10\text{‰}$, $\delta^{15}\text{N}$ (AIR) = $4.26 \pm 0.12\text{‰}$) and/or USGS88 (marine collagen, $\delta^{13}\text{C}$ (V-PDB) = $-16.06 \pm 0.07\text{‰}$, $\delta^{15}\text{N}$ (AIR) = $14.96 \pm 0.14\text{‰}$). Precision is $\pm 0.2\text{‰}$ for $\delta^{15}\text{N}$ and $\pm 0.1\text{‰}$ for $\delta^{13}\text{C}$.

For bioapatite analysis, bone samples were grounded with an agate mortar and pestle and processed in the Environmental Isotope Laboratory from the University of Arizona (USA). In this case, bone samples were cleaned in distilled water with an ultrasonic cleaner and powdered using a mortar and pestle. Samples weighing ~ 10 mg each were soaked for 24–72 h in a 2% sodium hypochlorite solution to remove the organic material. Then, the samples were treated with 0.1 M acetic acid to remove exogenous carbonates. The samples were also allowed to react with dehydrated phosphoric acid and silver (silver removes the sulfur gases from the evolved CO₂) at 70°C in the KIEL-III Sample Preparation system. The $\delta^{13}\text{C}$ values of the resultant CO₂ were measured using the Finnigan MAT252 Isotope Ratio Mass Spectrometer. The calibration of the isotopic ratios was based on repeated measurements of NBS-19 and NBS-18 with a precision of $\pm 0.08\text{‰}$ for $\delta^{13}\text{C}$ (1 σ).

Only individuals with valid isotope values of collagen were included in the analysis. The reliability of collagen was validated following current accepted conventional preservation criteria: C/N ratio between 2.9 and 3.6 (DeNiro, 1985) and wt%C of 26%–44% and wt%N of 11%–16% (Van Klinken, 1999). We used a subsample of 10 individuals to assess the preservation of bioapatite (i.e., mineralogy and crystallinity) with ATR-FTIR.

ATR-FTIR screening was conducted at the Laboratory of Molecular Spectroscopy, Servei de Química—Universitat Autònoma de Barcelona using a Bruker Alpha II FTIR compact spectrometer, coupled to an Eco-ATR. Spectra of 1 mg of bone powder were collected in absorbance (A) mode with a spectral range of 400 to 4,000 cm⁻¹ (V), for 100 scans and a resolution of 8 cm⁻¹. Spectra generation and baseline corrections were performed with OPUS 7.8 software. To evaluate bioapatite diagenesis, we assessed five indexes (IRSF, Infrared Splitting Factor; C/P, Carbon/Phosphate; C/C, Carbon/Carbon; BPI, Type B Phosphate

index; API, Type A Phosphate index) relative to conventional values for well-preserved archaeological samples (France et al., 2020). See [Supplementary material 1: S4](#) for ATR-FTIR raw data and indexes.

Isotopic analysis and BSIMM models

To identify trends of isotope values we used the “classic” scatterplots of isotopic values (i.e., $\delta^{13}\text{C}_{\text{coll}}$ vs. $\delta^{15}\text{N}$; $\delta^{13}\text{C}_{\text{coll}}$ vs. $\delta^{13}\text{C}_{\text{ap}}$) and rKin -Standard Ellipse Areas (Albeke, 2017). After evaluation for normal distribution with Shapiro–Wilk test for normality ($\alpha = 0.05$), descriptive statistics of isotope values and comparisons by sex (i.e., males, females and undetermined) and wide age-categories (i.e., preadults and adults) were performed using Kruskal–Wallis ($\alpha = 0.05$) and Mann–Whitney ($\alpha = 0.05$) tests with SPSS v.29 (Microsoft®). Kernel Density analysis and graphics were performed with the function *geom_density()* of the ggplot2 package in R environment.

The BSIMM software FRUITS (v. 2.1.1 Beta program; Fernandes et al., 2014, 2015), was employed to estimate the proportional calorie contribution of different food sources to the diet using three dietary proxies $\delta^{13}\text{C}_{\text{coll}}$, $\delta^{15}\text{N}$ and $\delta^{13}\text{C}_{\text{ap}}$ (see [Supplementary material 2](#) for the FRUITS model’s implementation). In this research, we run individuals’ estimations. The *consumer data* for individuals consist of their $\delta^{13}\text{C}_{\text{coll}}$, $\delta^{15}\text{N}_{\text{coll}}$, and $\delta^{13}\text{C}_{\text{ap}}$ isotopic values. For Vichama, as a group, we use the average of isotope values and the standard error of the mean.

We charged our model with four potential food sources consumed (*Food groups*), with their respective composition of macro-nutrients (*Food fractions*: bulk, protein, and energy): terrestrial fauna, providing proteins and lipids; marine fauna, providing proteins and lipids; and C₃ and C₄ plants, providing carbohydrates and proteins. The isotopic mean values of these food groups come from previous dietary reconstructions for the Andean Central Coast (Pezo-Lanfranco et al., 2022; see [Supplementary material 1: S7](#)).

In the Central Coast of Peru, C₃ plants (including tubers, legumes, annuals, and fruits) have mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of $-25.7 \pm 2.1\text{‰}$ and $+5.3 \pm 3.2\text{‰}$, respectively. The C₄ plants (restricted to *Zea mays* in such cases) have mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of $-11.3 \pm 1.4\text{‰}$ and $+7.3 \pm 3.0\text{‰}$. The CAM plants have $\delta^{13}\text{C}$ mean values of $-10.8 \pm 0.2\text{‰}$ that overlap with C₄, and $\delta^{15}\text{N}$ of $+3.8 \pm 0.4\text{‰}$. Terrestrial faunal (e.g., cervids, rodents, and camelids) show $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}$ mean values ranging between $-17.5 \pm 3.2\text{‰}$ and $+9.0 \pm 3.1\text{‰}$. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ mean values for marine fauna (including fishes, little fishes such as anchovy and sardines, mollusks, and marine birds and mammals from modern and archaeological origin) are $-11.9 \pm 2.1\text{‰}$ and $+13.2 \pm 3.0\text{‰}$, respectively (Pezo-Lanfranco and Colonese, 2024). The $\delta^{13}\text{C}$ values from modern fauna specimens were corrected for the “fossil fuel effect” adjusting the values by $+1.5\text{‰}$ (Marino and McElroy, 1991). To avoid issues with preservation (Szpak and Chiou, 2019), only values from modern plants were used to feed the model.

Isotope fractionation factors, derived from experimental studies, were established at $+4.8 \pm 0.5\text{‰}$ between diet and collagen, $+10.1 \pm 0.5\text{‰}$ between diet and apatite, $+5.5 \pm 0.5\text{‰}$ for $\delta^{15}\text{N}$ diet to collagen (Fernandes et al., 2014, 2015).

The weighted values of each fraction of macronutrients (lipids, carbohydrates, and proteins) followed published parameters (Fernandes et al., 2014, 2015; Pezo-Lanfranco et al., 2022; Pezo-Lanfranco and Colonese, 2024). The values of $\delta^{13}\text{C}_{\text{ap}}$ represent the total carbon mix in the diet. Therefore, we use the same bulk value for each food group. Terrestrial and marine fauna $\delta^{13}\text{C}$ bulk values were estimated as a weighted mean of lipid and protein $\delta^{13}\text{C}$ values (Fernandes et al., 2014, 2015). For collagen, the carbon of the protein and energy routed to the total collagen was established at $74 \pm 4\%$ and 26% , respectively (Fernandes et al., 2012). We assumed that nitrogen was derived exclusively from proteins (100%). Lipids and carbohydrates were added to the model as “energy”. To integrate this combinatorial effect, we applied a “concentration-dependent” model (Fernandes et al., 2014, 2015).

Following previous reconstructions using FRUITS (Fernandes et al., 2014, 2015; Pezo-Lanfranco et al., 2022) the isotopic composition of each nutritional fraction (protein, carbohydrates, and lipids) was obtained from the mean values of $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{15}\text{N}_{\text{coll}}$ using the following fractionation factors: -2% ($\Delta^{13}\text{C}_{\text{protein-collagen}}$), -8% ($\Delta^{13}\text{C}_{\text{lipids-collagen}}$), and $+2\%$ ($\Delta^{15}\text{N}_{\text{protein-collagen}}$) for terrestrial mammals and -1% ($\Delta^{13}\text{C}_{\text{protein-collagen}}$), -7% ($\Delta^{13}\text{C}_{\text{lipids-collagen}}$), and $+2\%$ ($\Delta^{15}\text{N}_{\text{protein-collagen}}$) for marine animals. For plants, the offsets were -2% ($\Delta^{13}\text{C}_{\text{bulk-protein}}$) and $+0.5\%$ ($\Delta^{13}\text{C}_{\text{bulk-lipids}}$), while for the $\delta^{15}\text{N}$ value of plant protein, the known value of $\delta^{15}\text{N}$ recorded for the plant was assumed. The carbon weight (concentrations) of each food fraction (protein and energy) from each food group was calculated according to its macronutrient composition (Fernandes et al., 2014, 2015; Pezo-Lanfranco et al., 2022; see details in Supplementary material 2). A physiological, conservative, and acceptable range of protein consumption stipulated between 5% and 45% of the total calories was charged as “prior” (Fernandes et al., 2014). The estimates of FRUITS models reflect carbon content or equivalent calorie contributions expressed as relative contributions (adding up to 1 or 100%) with an associated 1σ uncertainty (Fernandes et al., 2015).

Finally, a Kullback–Leibler divergence test (Lyman, 2008) was performed to estimate the statistical difference between the probability distributions of the four food groups between periods (EF-1 vs. LIP). This test was executed with the *Entropy* package of the R environment (Supplementary material 2).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

LP-L: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Conceptualization, Data curation, Investigation, Project

administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AP-B: Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. TA: Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. MM: Investigation, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. MY: Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. MG: Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. LM: Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. JA: Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. AD: Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. PN: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ACC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing. RS: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fearc.2025.1611071/full#supplementary-material>

References

- Aguilar, M. A. (2006). "Surgimiento de las sociedades complejas en los andes centrales," in *Una perspectiva desde el valle de Huaura, Perú. Licentiate Monography* (Lima: Universidad Nacional Federico Villarreal).
- Albeke, S. E. (2017). "rKIN: (kernel) isotope niche estimation," in *R Package Version 0.1*. Available online at: <https://cran.r-project.org/web/packages/rKIN/rKIN.pdf>
- AlQahtani, S. J., Hector, M. P., and Liversidge, H. M. (2010). Brief communication: the London atlas of human tooth development and eruption. *Am. J. Phys. Anthropol.* 142, 481–490. doi: 10.1002/ajpa.21258
- Ambrose, S. H., and Norr, L. (1993). "Experimental evidence for the relationship of carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate," in *Prehistoric Human Bone: Archaeology at the Molecular Level* (Berlin: Springer), 1–37.
- Buikstra, J., and Ubelaker, D. (1994). *Standards for Data Collection from Human Skeletal Remains*. Fayetteville: Arkansas Archeological Survey Research Series, No.44.
- Cadwallader, L., Beresford-Jones, D. G., Whaley, O., and O'Connell, T. (2012). The sign of maize? A reconsideration of what $\delta^{13}\text{C}$ values say about Paleodiet in the Andean Region. *Hum. Ecol.* 40, 487–509. doi: 10.1007/s10745-012-9509-0
- Caramanica, A., Huaman Mesa, L., Morales, C. R., Huckleberry, G., Castillo, L. J., and Quilter, J. (2020). El Niño resilience farming on the north coast of Peru. *Proc. Natl. Acad. Sci. U.S.A.* 117:24127. doi: 10.1073/pnas.2006519117
- Cárdenas, M. (1977). *Informe Preliminar del Trabajo de Campo en el Valle de Huaura (Departamento de Lima)*. Lima: Instituto Riva Agüero, Seminario de Arqueología, PUCP.
- Carré, M., Sachs, J. P., Purca, S., Schauer, A. J., Braconnot, P., Angeles-Falcón, R., et al. (2014). Holocene history of ENSO variance and asymmetry in the eastern tropical Pacific. *Science* 345, 1045–1048. doi: 10.1126/science.1252220
- Cheung, C., and Szpak, P. (2021). Interpreting past human diets using stable isotope mixing models. *J. Archaeol. Method Theory* 28, 1106–1142. doi: 10.1007/s10816-020-09492-5
- Chisholm, B. S., Nelson, D. E., and Schwarcz, H. P. (1982). Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science* 216, 1131–1132. doi: 10.1126/science.216.4550.1131
- Chu, A. (2011). *Household organization and social inequality at Bandurria, a Late Preceramic village in Huaura, Peru* (PhD. Dissertation). University of Pittsburgh, Pittsburgh, PA, United States.
- Contreras, D. A. (2010). Landscape and environment: Insights from the Prehispanic Central Andes. *J. Arch. Res.* 18, 241–288. doi: 10.1007/s10814-010-9038-6
- Coutts, K., Chu, A., and Krigbaum, J. (2011). Paleodiet in Late Preceramic Peru: Preliminary Isotopic data from Bandurria. *J. Island Coast. Archaeol.* 6, 196–210. doi: 10.1080/15564894.2011.586086
- Creamer, W., Ruiz, A., Perales, M., and Haas, J. (2013). The Fortaleza Valley, Peru: Archaeological investigation of late archaic sites (3000–1800 BC). *Field. Anthropol.* 44, 1–108. doi: 10.3158/0071-4739-44.0.1
- DeNiro, M. J. (1985). Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to paleodietary reconstruction. *Nature* 317, 806–809. doi: 10.1038/317806a0
- DeNiro, M. J., and Epstein, S. (1981). Influence of diet on the distribution of nitrogen isotopes in animals. *Geochim. Cosmochim. Acta* 45, 341–351. doi: 10.1016/0016-7037(81)90244-1
- Dillehay, T. D. (2017). *Where the Land Meets the Sea: Fourteen Millennia of Human History at Huaca Prieta, Peru*. Austin: University of Texas Press.
- Dillehay, T. D., Elling, H., and Rossen, J. (2005). Preceramic irrigation canals in the Peruvian Andes. *Proc. Natl. Acad. Sci. U.S.A.* 102, 17241–17244. doi: 10.1073/pnas.0508583102
- Dillehay, T. D., and Kolata, A. L. (2004). Long-term human response to uncertain environmental conditions in the Andes. *Proc. Natl. Acad. Sci. U.S.A.* 101, 4325–4330. doi: 10.1073/pnas.0400538101
- Dillehay, T. D., Rossen, J., Andres, T. C., and Williams, D. E. (2007). Preceramic adoption of peanut, squash, and cotton in northern Peru. *Science* 316, 1890–1893. doi: 10.1126/science.1141395
- Engel, F. A. (1987). "De las Begonias al Maíz," in *Vida y Producción en el Perú Antiguo* (Lima: Centro de Investigaciones de Zonas Áridas CIZA, Universidad Nacional Agraria La Molina).
- Fernandes, R., Grootes, P. M., Nadeau, M. J., and Nehlich, O. (2015). Quantitative diet reconstruction of a neolithic population using a Bayesian mixing model (FRUITS): The case study of Ostorf (Germany). *Am. J. Phys. Anthropol.* 158, 325–340. doi: 10.1002/ajpa.22788
- Fernandes, R., Millard, A. R., Brabec, M., Nadeau, M. J., and Grootes, P. M. (2014). Food reconstruction using isotopic transferred signals (FRUITS): a Bayesian model for diet reconstruction. *PLoS ONE* 9:e87436. doi: 10.1371/journal.pone.0087436
- Fernandes, R., Nadeau, M. J., and Grootes, P. M. (2012). Macronutrient-based model for dietary carbon routing in bone collagen and bio-apatite. *Archaeol. Anthropol. Sci.* 4, 291–301. doi: 10.1007/s12520-012-0102-7
- France, C. A. M., Sugiyama, N., and Aguayo, E. (2020). Establishing a preservation index for bone, dentin, and enamel bioapatite mineral using ATR-FTIR. *J. Arch. Rep.* 33, 102551. doi: 10.1016/j.jasrep.2020.102551
- Goldberg, A., Mychajliw, A. M., and Hadly, E. A. (2016). Post-invasion demography of prehistoric humans in South America. *Nature* 532, 232–235. doi: 10.1038/nature17176
- Grobman, A., Bonavia, D., Dillehay, T. D., Piperno, D. R., Iriarte, J., and Holst, I. (2012). Preceramic maize from Paredones and Huaca Prieta Peru. *Proc. Natl. Acad. Sci. U. S. A.* 109, 1755–1759. doi: 10.1073/pnas.1120270109
- Haas, J., and Creamer, W. (2006). Crucible of Andean Civilization: The Peruvian coast from 3000 to 1800 BC. *Curr. Anthropol.* 47, 745–775. doi: 10.1086/506281
- Haas, J., Creamer, W., Huamán, L., Goldstein, D., Reinhard, K., and Vergel, C. (2013). Evidence for maize (*Zea mays*) in the Late Archaic (3000–1800 B.C.) in the Norte Chico region of Peru. *Proc. Natl. Acad. Sci. U.S.A.* 110, 4945–4949. doi: 10.1073/pnas.1219425110
- Heaton, T., Köhler, P., Butzin, M., Bard, E., Reimer, R., Austin, W., et al. (2020). Marine20 - the marine radiocarbon age calibration curve (0–55,000 cal BP). *Radiocarbon* 62, 779–820. doi: 10.1017/RDC.2020.68
- Hedges, R. E. M., and Reynard, L. M. (2007). Nitrogen isotopes and the trophic level of humans in archaeology. *J. Archaeol. Sci.* 34, 1240–1251. doi: 10.1016/j.jas.2006.10.015
- Herbert, T. (2003). "Alkenone paleotemperature determinations," in *Treatise on Geochemistry: The Oceans and Marine Geochemistry*, ed. H. Elderfeld (New York: Elsevier), 391–432.
- Hogg, A., Heaton, T., Hua, Q., Palmer, J., Turney, C., Southon, J., et al. (2020). SHCal20 southern hemisphere calibration, 0–55,000 years cal BP. *Radiocarbon* 62, 759–778. doi: 10.1017/RDC.2020.59
- IMARPE (2010). *Informe: Delimitación y caracterización de bancos naturales de invertebrados bentónicos comerciales y áreas de pesca artesanal en la región Lima entre Punta Litera-Playa Grande, Barranca y Huaura de la Region Lima*. Lima: Instituto del Mar del Perú.

- INRENA (2005). *Inventario y monitoreo de las aguas subterráneas en el valle Huaura*. Anexos (Lima: Autoridad Nacional del Agua). Available online at: <https://hdl.handle.net/20.500.12543/2037> (Accessed July 7, 2023).
- Jim, S., Ambrose, S., and Evershed, R. P. (2004). Stable carbon isotopic evidence for differences in the dietary origin of bone cholesterol, collagen, and apatite: implications for their use in paleodietary reconstruction. *Geochim. Cosmochim. Acta* 68, 61–72. doi: 10.1016/S0016-7037(03)00216-3
- Kellner, C. M., and Schoeninger, M. J. (2007). A simple carbon isotope model for reconstructing human diet. *Am. J. Phys. Anthropol.* 133, 1112–1127. doi: 10.1002/ajpa.20618
- Kennett, D. J., and Marwan, N. (2015). Climatic volatility, agricultural uncertainty, and the formation, consolidation and breakdown of preindustrial agrarian states. *Phylos. T. R. Soc. A* 373:20140458. doi: 10.1098/rsta.2014.0458
- Leclerc, E. L. (2023). Coast and highland paleoclimate of the north-central Peruvian Andes and its influence on coastal water availability and cultural development, 6000 to 2000 cal BP. *Quat. Sci. Rev.* 314:108209. doi: 10.1016/j.quascirev.2023.108209
- León, E. (2013). *14,000 años de alimentación en el Perú*. Lima: Universidad de San Martín de Porres.
- Lima, M., Gayó, E. M., Gurruchaga, A., Estay, S. A., and Santoro, C. M. (2023). 1000 years of population, warfare, and climate change in pre-Columbian societies of the Central Andes. *PLoS ONE* 18:e0278730. doi: 10.1371/journal.pone.0278730
- Loubere, P., Creamer, W., and Haas, J. (2013). Evolution of the El Niño–Southern Oscillation in the late Holocene and insolation driven change in the tropical annual SST cycle. *Glob. Planet. Change* 100:129e144. doi: 10.1016/j.gloplacha.2012.10.007
- Lyman, R. L. (2008). *Quantitative Paleozoology*. Cambridge: Cambridge University Press.
- Mächtle, B., and Eitel, B. (2013). Fragile landscapes, fragile civilizations - how climate determined societies in the pre-Columbian south Peruvian Andes. *Catena* 103, 62–73. doi: 10.1016/j.catena.2012.01.012
- Makowski, K. (2023). Pre-Hispanic andean urbanism and its 'anti-urban' peculiarities. *J. Urban Archaeol.* 8, 165–196. doi: 10.1484/J.JUA.5.135664
- Marino, B. D., and McElroy, M. B. (1991). Isotopic composition of atmospheric CO₂ inferred from carbon in C₄ plant cellulose. *Nature* 349, 127–131. doi: 10.1038/349127a0
- Minagawa, M., and Wada, E. (1984). Stepwise enrichment of $\delta^{15}\text{N}$ along food chains: further evidence and the relation between $\delta^{15}\text{N}$ and animal age. *Geochim. Cosmochim. Acta* 48, 1135–1140. doi: 10.1016/0016-7037(84)90204-7
- Moseley, M. E. (1975). *The Maritime Foundations of Andean Civilization*. Menlo Park, CA: Cummings Publishing Company.
- Orloff, C. R. (2022). Caral, South America's Oldest City (2600–1600 BC): ENSO environmental changes influencing the late archaic period site on the North Central Coast of Peru. *Water* 14:1403. doi: 10.3390/w14091403
- Pezo-Lanfranco, L., and Colonese, A. C. (2024). The role of farming and fishing in the rise of social complexity in the Central Andes: a stable isotope perspective. *Sci. Rep.* 14:4582. doi: 10.1038/s41598-024-55436-4
- Pezo-Lanfranco, L., Crispin, A., Machacuay, M., Novoa, P., and Shady, R. (2020). Isotopic evidence of weaning behaviors from farming communities of the Peruvian North-Central Coast. Insights into the demography of the transition from the middle to the late formative periods (500–400 B.C.). *Bioarchaeol. Int.* 3–4, 191–216. doi: 10.5744/bi.2020.3019
- Pezo-Lanfranco, L., Machacuay, M., Novoa, P., Peralta, R., Mayer, E., Eggers, S., et al. (2022). The diet at the onset of the Andean Civilization: New stable isotope data from Caral and Áspero, North-Central Coast of Peru. *Am. J. Biol. Anthropol.* 177, 402–424. doi: 10.1002/ajpa.24445
- Pezo-Lanfranco, L., Pezo-Lanfranco, S., and Eggers, S. (2009). Exostosis auditiva como marcador osteológico de actividad acuática en poblaciones formativas de la Costa Norte del Perú. *Paleopatología* 6, 1–18. Available online at: <https://asociacionpaleopatologia.es/revista-paleopatologia/#andISSN1579-0606>
- Phillips, D. L. (2012). Converting isotope values to diet composition: the use of mixing models. *J. Mammal.* 93, 342–352. doi: 10.1644/11-MAMM-S-158.1
- Piperno, D. R., and Dillehay, T. D. (2008). Starch grains on human teeth reveal early broad crop diet in northern Peru. *Proc. Natl. Acad. Sci. U.S.A.* 105, 19622–19627. doi: 10.1073/pnas.0808752105
- Salvattici, R., Gutiérrez, D., Field, D., Sifeddine, A., Ortlieb, L., Bouloubassi, I., et al. (2014). The response of the Peruvian Upwelling Ecosystem to centennial-scale global change during the last two millennia. *Clim. Past* 10, 715–731. doi: 10.5194/cp-10-715-2014
- Salvattici, R., Gutiérrez, D., Sifeddine, A., Ortlieb, L., Druffel, E., Boussafir, M., et al. (2016). Centennial to millennial-scale changes in oxygenation and productivity in the eastern tropical South Pacific during the last 25000 years. *Quat. Sci. Rev.* 131, 102–117. doi: 10.1016/j.quascirev.2015.10.044
- Salvattici, R., Schneider, R. R., Blanz, T., and Mollier-Vogel, E. (2019). Deglacial to Holocene ocean temperatures in the Humboldt current system as indicated by alkenone paleothermometry. *Geophys. Res. Lett.* 46, 281–292. doi: 10.1029/2018GL080634
- Sandweiss, D. H., Shady, R., Moseley, M., Keefer, D. K., and Orloff, C. R. (2009). Environmental change and economic development in coastal Peru between 5,800 and 3,600 years ago. *Proc. Natl. Acad. Sci. USA* 106, 1359–1363. doi: 10.1073/pnas.0812645106
- Schoeninger, M. J. (2010). Diet reconstruction and ecology using stable isotope ratios, in *A companion to Biological Anthropology* (Hoboken, NJ: Wiley-Blackwell), 445–464.
- Schoeninger, M. J., and DeNiro, M. J. (1984). Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochim. Cosmochim. Acta* 48, 625–639. doi: 10.1016/0016-7037(84)90091-7
- Schoeninger, M. J., DeNiro, M. J., and Tauber, H. (1983). Stable nitrogen isotope ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science* 220, 1381–1383. doi: 10.1126/science.6344217
- Schoeninger, M. J., and Reitsem, L. J. (2023). "Diet reconstruction and ecology," in *A Companion to Biological Anthropology*, ed. C. S. Larsen (Malden: Wiley-Blackwell), 510–526.
- Scholz, F., McManus, J., Mix, A., Hensen, C., and Schneider, R. (2014). The impact of ocean deoxygenation on the ocean's iron supply. *Nat. Geosci.* 7, 433–437. doi: 10.1038/ngeo2162
- Shady, R. (2006a). La civilización Caral: sistema social y manejo del territorio y sus recursos. Su trascendencia en el proceso cultural andino. *Bol. Arqueol. PUCP* 10, 59–89. doi: 10.18800/boletindearqueologiapucp.200601.004
- Shady, R. (2006b). "America's first city? The case of Late Archaic Caral," in *Andean Archaeology III*, eds. D. W. Isbell, and H. Silverman (Boston: Springer), 28–66.
- Shady, R. (2006c). "Caral-Supe and the North-Central area of Peru: The history of maize in the land where Civilization came into being," in *Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize*, eds. J. Staller, R. Tykot, and B. Benz (Cambridge, MA: Academic Press), 381–402.
- Shady, R. (2018). *El sistema social de Caral y su trascendencia: El manejo transversal del territorio, la complementariedad social y política y la interacción intercultural* (Lima: Nayra Kunan Pacha, Revista de Arqueología Social, Proyecto Especial Arqueológico Caral-Supe), 19–90.
- Shady, R., and Cáceda, D. (2008). *Áspero, la ciudad pesquera de la civilización Caral-Supe, recuperamos su historia para vincularla con nuestro presente Proyecto Especial Arqueológico Caral-Supe*. Lima: Instituto Nacional de Cultura.
- Shady, R., Crispin, A., and Quispe, E. (2008). "Vichama de Végueta comparte con Caral 5000 años de Identidad Cultural," in *Proyecto Especial Arqueológico Caral-Supe* (Lima: Instituto Nacional de Cultura).
- Shady, R., Haas, J., and Creamer, W. (2001). Dating Caral, a Pre-ceramic urban center in the Supe Valley on the central coast of Peru. *Science* 292, 723–726. doi: 10.1126/science.1059519
- Shady, R., Machacuay, M., Quispe, E., Novoa, P., and Leyva, C. (2015). *Vichama, historia social de la Civilización en Végueta. 3800 años de memoria colectiva de nuestros ancestros de Vichama ante el cambio climático*. Lima: Biblioteca Nacional del Perú.
- Shoji, K., Vásquez, V. F., and Rosales, T. E. (2023). Starch grains on human teeth as evidence for 4000 BCE potato consumption at the Cruz Verde site, northern coast of Peru. *J. Archaeol. Sci. Rep.* 51:104152. doi: 10.1016/j.jasrep.2023.104152
- Stuiver, M., and Reimer, P. J. (1993). CALIB rev. 8. *Radiocarbon* 35, 215–230. doi: 10.1017/S0033822200013904
- Szpak, P., and Chiou, K. L. (2019). A comparison of nitrogen isotope compositions of charred and desiccated botanical remains from northern Peru. *Veg. Hist. Archaeobot.* 29, 527–538. doi: 10.1007/s00334-019-00761-2
- Tello, J. C. (2004). La Muralla de Santa. *Arqueología y Sociedad* 15, 11–32. doi: 10.15381/arqueolsoc.2004n15.e12731
- Tung, T. A., Dillehay, T. D., Feranec, R., and DeSantis, L. R. G. (2021). Early specialized maritime and maize economies on the north coast of Peru. *Proc. Natl. Acad. Sci. U. S. A.* 117, 32308–32319. doi: 10.1073/pnas.2009121117
- Van Klinken, G. J. (1999). Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *J. Arch. Sci.* 26, 687–695. doi: 10.1006/jasc.1998.0385
- Vega-Centeno, R. (2005). *Ritual and Architecture in a Context of Emergent Complexity: A Perspective from Cerro Lampay, a Late Archaic Site in the Central Andes* (PhD. Dissertation). The University of Arizona, Tucson, AZ, United States.
- Wefer, G., Fischer, G., and Iversen, M. (2015). "Export production," in *Encyclopedia of Marine Geosciences*, eds. J. Harff, M. Meschede, S. Petersen, and J. Thiede (Dordrecht: Springer).
- Wilson, K. M., McCool, W. C., Brewer, S. C., Zamora-Wilson, N., Schryver, P. J., Lamson, R. L. F., et al. (2022). Climate and demography drive 7000 years of dietary change in the Central Andes. *Sci. Rep.* 12:2026. doi: 10.1038/s41598-022-05774-y

- Wilson, K. M., McCool, W. C., and Coltrain, J. B. (2024). Climate and oceanic condition changes influence subsistence economic adaptation through intensification on the Central Andean coasts. *Quat. Int.* 689, 79–92. doi: 10.1016/j.quaint.2023.07.002
- Yseki, M., Crispin, A., Abad, T., Prado, A., Novoa, P., and Shady, R. (2024). First comprehensive macroremains analysis of edible plants in Vichama site, Peru during the Early Formative Period I (1800–1500 BCE). *Veg. Hist. Archaeobot.* 34, 91–100. doi: 10.1007/s00334-024-01004-9
- Yseki, M., Pezo-Lanfranco, L., Machacuay, M., Novoa, P., and Shady, R. (2023). Analysis of starch grains trapped in human dental calculus in Áspero, Peru during the Initial Formative Period (3000–1800 BCE). *Sci. Rep.* 13:14143. doi: 10.1038/s41598-023-41015-6
- Yseki, M., Turcq, B., Caquineau, S., Salvatelli, R., Solis, J., Skilbeck, C. G., et al. (2022). Millennial variability of terrigenous transport to the central–southern Peruvian margin during the last deglaciation (18–13 kyr BP). *Clim. Past.* 18, 2255–2269. doi: 10.5194/cp-18-2255-2022
- Zechenter, E. (1988). *Subsistence strategies in the Supe Valley of the Peruvian Central Coast During the Complex Preceramic and Initial Periods* (PhD. Dissertation). University of California, Los Angeles, Los Angeles, CA, United States.