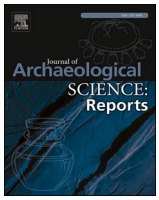
Journal of Archaeological Science: Reports 58 (2024) 104723

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep



Preadult diets in the prehistoric Lima-city: Stable isotopes from Huaca 20 (620–780 CE), Maranga Complex, Peru

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ARTICLE INFO

Keywords:
Andean archaeology
Lima Culture
Early Intermediate Period
Middle Horizon
Stable isotopes
Human diet

ABSTRACT

Using stable isotope and Bayesian Mixing Models, this study aims to understand the preadult dietary patterns of human individuals from Huaca 20 (H20, 620–780 CE), a residential sector of the main urban center in the lower Rimac Valley of the Peruvian Central Coast. Due to preservation issues, a practical approach was employed to understand the diet of this population, using data for $\delta^{13}C$ and $\delta^{15}N$ obtained from the dentine of anatomic tooth segments of 20 adult individuals, which were analyzed by sex and broad life-stages (i.e., infant, child, adolescent). We then conducted individual paleodietary reconstructions using a Bayesian Mixing Model to obtain the quantitative contribution of four food groups. The results indicate that this population relied on a mixed diet mainly composed of C_4 (maize) and C_3 resources complemented with marine protein in variable proportions, and minimal contributions of terrestrial protein. Maize and C_3 resources were the main foods during infancy and childhood of these adults, whereas the diet during adolescence shows more marine protein, possibly more similar to the adult diet of this community. This isotopic evidence from Huaca 20 suggests the use of specific infant feeding strategies.

1. Introduction

1.1. Archaeological background

Preadult diets are crucial for health, growth, and survival. Children require a nutritious diet that is suitable for their developing digestive systems. In human groups preadult diets (weaning and post-weaning diets) can be particularly informative about a population's diet and childcare behaviors, which, in turn, can be a modulating factor of population growth (Humphrey, 2014). The subject is especially relevant for the study of farming development, urbanization processes and political transitions, topics that we approach in this study.

Archaeological evidence suggests the Peruvian Central Coast was densely populated during the Early Intermediate Period (1–600 CE) and Middle Horizon (600–1000 CE), corresponding to the flourishing of the Lima Culture, the expansion of settlements, and the development of urban centers (Goldhausen, 2001). This growth is particularly evident in the Maranga Complex (ca. 250–780 CE), the main settlement of the lower Rímac Valley, especially during the Late Lima Phase (Kaulicke, 2000) dated to the beginning of the Middle Horizon (620–780 CE: Vega-Centeno et al., 2021). This period is characterized by the increased scale and complexity of Lima's public buildings at various sites in the valley (Canziani, 2009; Narváez, 2013; Cornejo, 2021).

Maranga, probably an urban and political center (150 ha), was located in the lower valley on the left bank of the Rimac River, less than 3 km from the coast, in an area well-suited for agriculture and close to irrigation canals (Fig. 1). The Rimac Valley is one of the most productive valleys in the Pacific Coastal Desert, with its lower sector (0–150 m above sea level) offering a wide alluvial fan suitable for cultivation, with water available year-round. With temperatures in this area ranging between 15 and 22 °C, and an average annual rainfall of 200 mm (ONERN, 1975; Mauricio, 2012), this part of the valley would have been highly attractive for settlement by farming and fishing communities during the pre-Hispanic period.

The regional dietary evidence for the Late Lima phase includes high quantities of maize, beans, and chili peppers, possibly with more plant

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https://doi.org/10.1016/j.jasrep.2024.104723
Received 24 May 2024; Received in revised form 5 August 2024; Accepted 8 August 2024
Available online 16 August 2024

intake in the middle valleys and more fish intake near the sea (Cleary, 2019; Mauricio, 2012). For instance, in the roughly contemporaneous sit of Huaca Pucllana in the lower valley 7 km far from Maranga, edible plants included maize, chili peppers, beans, pumpkin, gourds, *achira* and other tubers, and several fruits (guava, *pacay* and *lucuma*), and while animal proteins were derived from camelids and 62 marine species (Vargas, 2015).

Paleodietary reconstructions based on stable isotopes from other sites in the Rimac Valley and neighboring valleys, spanning from 200 BCE to the 16th century CE, reveal the importance of maize during the Maranga period (Williams and Murphy, 2013; Gerdau-Radonić et al., 2015; Marsteller, 2015). Knowledge about individual diets at Lima during this period, however, is limited and based on inferences from plant and fauna macro-remains. In addition, very little is known about dietary segregations and differential access to food sources by distinct members of the community, including infants (Williams, 2005).

Using stable isotopes and Bayesian Mixing Models (BISMMs), through an isobiographic approach, this study aims to shed light on the dietary nature of the Lima populations of the Maranga Complex. The goal is to identify and quantify the contribution of isotopically distinct food sources to infants, children, and adolescents, and to explore differences in parental investments by groups of the lower Rimac Valley during the transition from the Early Intermediate Period to the Middle Horizon.

1.2. The study site

The Sector Huaca 20 (hereafter H20) is a multipurpose archaeological locus of 0.63 ha. It is located in the periphery of the ancient Maranga Complex (WGS84 –12.065505, –77.081088, 65 m above sea level), and consists of a series of agglutinated dwellings in which people were also buried, minor public architecture, and remains of irrigation canals (Mac Kay, 2007; Mauricio et al., 2015; Vega Centeno and Epiquién, 2022).

Until the 1960's the area where H20 is located was a rural zone with agricultural fields, but now has been totally integrated to the urban area of the modern city of Lima. Although H20 and other *huacas* in this area are under protection of the Ministry of Culture of Peru, several other sites from different prehistoric periods have completely disappeared due to urban expansion, especially during the first half of 20th century (Canziani, 2009).

Nowadays, H20 is located within the boundaries of the Pontificia Universidad Católica del Perú, which has facilitated an exhaustive archaeological study over several field seasons. Since its initial exploration in the 1960's, H20 has been the subject of at least five archaeological projects that have excavated all of the architectural structures distributed in an area of more than 1.5 ha, revealing a rich and diverse (bio)archaeological record (Muro and González, 2015; Cleary, 2019; Vega-Centeno and Epiquién, 2022).

The spatial analysis of domestic units and the artifacts associated with domestic and funerary contexts suggest that H20 was inhabited by people dedicated to different tasks, such as pottery production, *chicha* (maize beer) preparation, and marine resource processing (Prieto, 2014; Vega-Centeno and Epiquién, 2022). Most burial tombs are poorly preserved; however, the burial patterns suggest that they correspond to common people, with no drastic differences in energy investment in the tombs and/or grave goods that would suggest social stratification.

Artifactual data suggests that fishing was the main economic activity of H20 (Prieto, 2014). The record includes a significant number of fishhooks in funerary (mainly of male individuals) and domestic contexts (Mauricio, 2012). At least 25 species of fish appear among the most exploited marine resources, especially small pelagic (*Odontesthes regia, Eugraulis ringens*) and middle-sized (*Paralonchurus peruanus*) fish, along with 14 species of bivalves and 16 species of gastropods from rocky and sandy ecosystems (*Crepipatella dilatata, Stramonita chocolata,* and *Mesodesma* sp.), as well as evidence of fish prepared in pots. There are a few remains of camelids, along with other unidentified mammals and birds (Mauricio, 2012; Prieto, 2014: 140).

According to Mauricio (2012: 179-261), the inventory also contains maize (*Zea mays*), beans (Fabaceae), potato (*Solanum* sp., probably *Solanum nigrum*), *aguaymanto* (*Physalis* sp.), and quinoa (*Chenopodium quinoa*), among other poorly preserved plant remains. It remains unclear if plants were fertilized, thus potentially modifying their nitrogen isotopic composition. Although the H20 individuals show relatively low frequencies of skeletal biological stress markers (Vega et al., 2015; Cleary, 2019), carious lesions are frequent, suggesting a high consumption of cariogenic carbohydrates (Cleary, 2019).

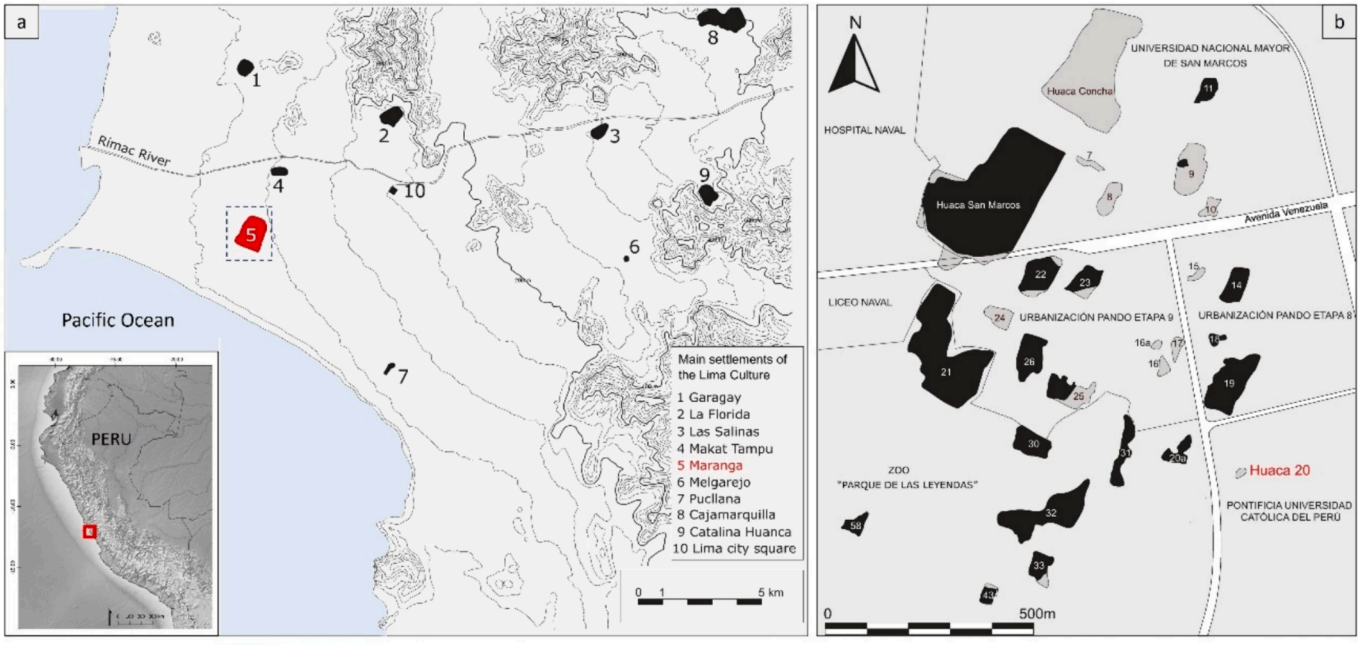

Fig. 1.A.) map of location of the maranga complex in the lower rimac valley, and other archaeological sites from the lima culture; b) Huaca 20 and other settlements (the numbers refer to the names of the Maranga *huacas* (e.g., Huaca 20, Huaca 20b; Huaca 11)) in the reconstructed limits of the Maranga Complex.

Stable carbon and nitrogen isotope analysis, which has never been performed on human individuals from H20, can provide additional data about the dietary composition and resource distribution among this population.

1.3. Dietary reconstruction with stable isotope analysis on human tissues

Stable carbon and nitrogen isotope analysis of bulk collagen ($\delta^{13}C$ and $\delta^{15}N$) is a well-established method to address past human and animal diets (DeNiro and Epstein, 1981; Schoeninger, 2010; Richards, 2020). During bone and tooth development, the collagen forms from amino acids derived from assimilated nutrients that an individual consumes over time. Recent studies suggest that around 76 % of carbon in collagen derives from dietary proteins, whereas the other 24 % can come from the whole diet. Nitrogen instead comes entirely from dietary proteins (Ambrose and Norr, 1993; Fernandes et al., 2012).

Based on the isotopic fractionation principle, stable isotopic analysis enables the identification of trophic level effects and the differentiation of dietary sources (i.e., plants and animals) from different ecosystems (Chisholm et al., 1982; Hedges and Reynard, 2007). The carbon values from collagen ($\delta^{13}C$) are approximately 5 ‰ higher than the $\delta^{13}C$ value of the dietary source. Diets based on C_3 plants can result in the consumer's collagen having mean $\delta^{13}C$ values of approximately −21 ‰ (plant values ranging from –33 ‰ to –22 ‰), whereas diets based exclusively on C_4 plants can reach mean values higher than −7‰ (plant values from −16 ‰ to −8‰), allowing for the differentiation between C_3 and C_4 plant sources (DeNiro and Epstein, 1978; Schoeninger et al., 1983). CAM (Crassulacean Acid Metabolism) plants, such as succulents and cacti, have intermediate values, closer to those of C_4 plants (O'Leary, 1988).

In diets without C_4 plants, the $\delta^{13}C$ values can also enable differentiation between terrestrial C_3 and marine food webs (Chisholm, 1989; Schoeninger et al., 1983). Nevertheless, when C_4 plants are part of the diet, this discrimination requires complementary analysis, such as the use of $\delta^{15}N$ or $\delta^{34}S$ (Hyland et al., 2021). Since trophic fractionation for $\delta^{15}N$ is well defined (3–6 ‰), it is possible to differentiate the high values of longer and more complex aquatic food webs from the lower values of terrestrial ones (DeNiro and Epstein, 1978; Chisholm, 1989; Schoeninger et al., 1983).

Until the introduction of Bayesian Stable Isotope Mixing Models (BSIMMs), graphic or linear isotopic ratio methods only allowed for a qualitative approach that did not clarify the quantitative contribution of each food source (e.g., C_3 and C_4 plants, marine and terrestrial proteins). BSIMMs allow for the inclusion of multiple proxies and sources of uncertainty such as variations in macronutrient composition, isotopic values of consumed items, fractionation (diet-to-consumer offsets), and nutrient routing factors, among others, enabling more reliable estimates of dietary composition as probability distributions (Fernandes et al., 2014, 2015).

1.4. Preservation issues in isotopic analyses in the Central Andes

Stable isotope analyses have been successfully employed to reconstruct diets in prehistoric populations in the Central Andes (Toyne and Turner, 2020; Pezo-Lanfranco and Colonese, 2024). Despite the excellent morphological preservation of human remains, a common issue in coastal Andes archaeology, however, has been the extensive degradation of bone collagen, especially in older samples (Ericson et al., 1989; Tykot et al., 2006; Gerdau-Radonić et al., 2015; Pezo-Lanfranco et al., 2022).

Due to H20's location near productive fields and the impacts of urbanization during the 20th century, the skeletons are poorly preserved (Vega et al., 2015; Cleary, 2019). Individuals were buried in terrain which underwent intense flooding and continuous irrigation, and the tombs were filled with a semi-compacted clay soil with pebbles (Mauricio et al., 2015). As expected, our pilot study did not retrieve any collagen from bones. In this study, we therefore analyzed the $\delta^{13}C$ and $\delta^{15}N$ values of segments of dentine collagen, the only possible source of viable collagen to reconstruct the diet of H20 individuals. Our aim was to determine the dietary components and relative proportions of protein and carbohydrates consumed during preadult life-stages of H20 individuals. Considering that dentine develops during preadult ages, we looked for heterogeneity (differences or inequalities) in access to different food types among preadult individuals and the possible relationship of these differences with sex (inferred from the adult bones) and different preadult life-stages (inferred from the sampled sections of the teeth).

2. Research questions and hypotheses

Studies on infant diets in ancient populations provide valuable insights into infant development and correlated demographic processes, such as parental investment and material conditions of life (Humphrey, 2014; Tsutaya and Yoneda, 2015). In addition, paleodietary reconstructions of preadults with well-defined biological sex may provide essential information to critically evaluate the existence of differences in food access according to gender and social status, central to understanding processes of internal hierarchization.

For this section of the Rimac Valley during this period, three questions remain unanswered: A) What was the type of subsistence system predominant in Maranga – farming, fishing, or mixed?; B) What was the relative contribution of the main sources of macronutrients (i.e., C_3 or C_4 (maize) plants, marine or terrestrial protein) to diets at the time?; and C) How did diet vary between preadult individuals according to sex, age, and social position? To examine the role of agricultural and marine products in the diet of H20 individuals, and the dependence of this population on one or more of the aforementioned production systems, it is necessary to determine intra-population differences in consumption of these resources.

Regarding to these questions, we hypothesize that A) the diet in H20 was mainly based on farming; B) maize was the primary source of calories in H20 diets, although a considerable dependence on marine protein was also expected; and C) diet varies with age, sex, and social position, with diets varying between preadult males and females in accordance with their social learning and economic activities, with females possibly eating more plant foods and males eating more fish. This hypothesis also predicts that infants consume more plant resources, probably maize, whereas older children and adolescents consume increasingly more animal protein. Several studies have stated that more independent children, such as those engaged in community activities, are able to obtain their own food. While this has been described for hunter-gatherers, it can be applied to fisher-farmers such as the H20 population. Identifying differences by social position, however, in this case is challenging because there is no evidence of differentiation demonstrated in the funerary patterns, and there is no evidence for the social importance of children.

3. Materials and methods

3.1. Human samples

Approximately 765 complete and incomplete individuals were recovered from H20 during several research seasons since 1991 (Cleary, 2019), with the osteological collection hosted in the laboratories of the Pontificia Universidad Católica del Perú. Authorization for study, sampling and exportation was provided by the Ministry of Culture of Peru (RD 000067–2023 DGM/MC).

Sex and age estimates were performed using standard procedures compiled by Buikstra and Ubelaker (1994), White and Folkens (2012), and Scheuer and Black (2000). Unfortunately, due to the aforementioned reasons, most skeletons showed poor preservation. Teeth were selected from the best-preserved individuals, with a total of 49

individuals (47 adults: 15 females, 11 males, and 21 undetermined; and 2 infants, both undetermined), dated to the Late Lima period (620–780 CE: Vega-Centeno et al., 2021), were sampled for isotopic analysis.

3.2. Dentine sampling and tissular-age attribution

The analysis of $\delta^{13}C$ and $\delta^{15}N$ of dentine collagen allows dietary reconstruction related to the age of tooth formation (Tsutaya and Yoneda, 2015). Depending on the tooth analyzed, we can obtain insights about diet at different preadult life-stages. We used $\delta^{13}C$ and $\delta^{15}N$ values from dentine bulk segments to reconstruct the diet of the H20 individuals and evaluate possible variations between life-stage categories that roughly correspond to growth and development levels (i.e., infant, toddler, child, adolescent) in preadults (Eerkens and Bartelink, 2013; Pezo-Lanfranco et al., 2018).

To avoid potential "contamination" of dentine isotope ratios with secondary or tertiary dentine, only healthy teeth (i.e., crowns without caries, roots without hypercementosis) were selected. For each tooth, the crown and roots were sectioned at the level of the anatomical neck using a low-speed rotatory device, and bulk roots were selected for the current study. When only dental crowns were available, they were halved, and the dentine was separated from the enamel (Fuller et al., 2003).

A total of 49 dentine samples were processed for collagen extraction. Although most roots were intact, some exhibited severe taphonomic damage and absent portions. Before collagen extraction, an age-range was attributed to each section (e.g., crown segment, $^1/_3$ root, ½ root, $^2/_3$ root, complete root) using dental development charts (AlQahtani et al. 2010, 2014). A median-age was then calculated for each dentine segment (Pezo-Lanfranco et al., 2018) to classify them into three broad life-stage categories: Infant (<6 years old), Child (6–11 years old), and Adolescent (>11 − 20 years old).

3.3. Laboratory methods for isotopic analysis

Collagen $\delta^{13}C$ and $\delta^{15}N$ values were analyzed at the Stable Isotope Laboratory of the *Institut de Ciencia i Tecnologia Ambientales* of the Universitat Autònoma de Barcelona (ICTA-UAB, Spain). First, sample surfaces were cleaned mechanically with a toothbrush and the external layer of cementum was removed with a scalpel. Then, collagen was extracted following a protocol modified from Longin (Brown et al., 1988). Root fragments were demineralized with 0.6 M HCl at 4 °C during several days, then treated with 0.05 M NaOH for humic acids removal, and rinsed with ultrapure H_2O (Milli-Q). The resultant solids were gelatinized with 0.001 M HCl (pH 3) at 80 °C for 48 h. The final solution was filtered using Polyethylene Ezee filters (9 mL, pore size 60–90 μm, Elkay Laboratories Ltd.), then frozen for at least 48 h at –20 °C and lyophilized. The resulting extracted collagen was combusted to obtain CO_2 and N_2 with a Thermo Scientific Flash IRMS EA system attached to a Thermo Scientific Delta V Advantage IRMS. Standardization was performed relative to the VPDB and AIR scales using two-point calibration based on multiple aliquots of international standards IAEA 600 and a keratin reference material ($\delta^{13}C$=–14.97; $\delta^{15}N$=13.52) for $\delta^{13}C$ and $\delta^{15}N$. Multiple replicates of the internal laboratory standard caffeine ($\delta^{13}C$=–37.35; $\delta^{15}N$=–2.47) were used to monitor data quality. Collagen was measured as a single sample. Precision was better than ±0.1 for $\delta^{13}C$ and ±0.2 for $\delta^{15}N$ (1σ).

3.4. Food groups from the Peruvian Central Coast

The reconstruction of local isotopic food webs provides support for inferences about diet and trophic positions, and enables the implementation of Bayesian mixing models. For this study, we used $\delta^{13}C$ and $\delta^{15}N$ values from 61 faunal (i.e., fish, mollusks, wild and domestic mammals) and plant (i.e., tubers, maize, fruits, beans) taxa potentially consumed by the populations of the Peruvian Central Coast. These previously reported values (Williams and Murphy, 2013; Gerdau-Radonić et al., 2015; Marsteller, 2015; Pezo-Lanfranco et al., 2022; see Supporting Information 1: ST1) were extracted from the South American Archaeological Isotopic Database (Pezo-Lanfranco et al., 2023, available at https://pandoradata.earth/dataset/saaid_v-2-0_2023).

To avoid issues related to preservation, we only used isotope values from modern plants (DeNiro and Hastorf, 1985; Szpak and Chiou, 2019), whereas marine and terrestrial fauna were from modern and archaeological contexts (Table 1 and Fig. 2). The $\delta^{13}C$ values from modern specimens were corrected for the "fossil fuel effect" adjusting the values by + 1.5 ‰ (Marino and McElroy, 1991). It is necessary to consider a few potential issues, such as the isotope values of modern plants and fauna not necessarily corresponding with the values of past specimens. For example, it is unclear if modern plants have been fertilized. Comparison with wild plant material from coastal Peru, the reported $\delta^{15}N$ values for these samples suggest the plants were not fertilized with animal dung (Szpak and Chiou, 2019).

3.5. Statistical analyses

After exploratory analysis for normality (Shapiro-Wilk test, $p < 0.05$, Supporting Information 1: ST3a) of $\delta^{13}C$ and $\delta^{15}N$ values, descriptive (mean, range, standard deviation, standard error of the mean) and inferential statistical analyses were performed to detect significant differences between sex and life-stage categories using ANOVA ($p < 0.05$ with HSD Tuckey as a post-hoc test, and Bonferroni Correction for multiple comparisons at $p < 0.017$). These tests were performed in SPSS v.29 (Microsoft®).

The proportional contribution of different food groups to the diet of each individual was estimated using the Bayesian Stable Isotope Mixing Model FRUITS (Food Reconstruction Isotopic Transferred Signals v. 2.1.1-Beta statistical package). This model enables the calculation of the most approximate posterior densities and probabilities of the carbon content or equivalent calorie contributions of each food type (Fernandes et al., 2014; Fernandes et al., 2015: 333).

Only individuals with reliable isotope values, according to standard criteria (DeNiro, 1985; Van Klinken et al., 1999), were included in the analysis. A weighted model of two proxies ($\delta^{13}C$, $\delta^{15}N$) with fractionation factors (offsets) based on nutrient concentrations in the respective food groups was applied (Fernandes et al., 2015). The *consumer data* for individuals are their isotopic values with an uncertainty of ±0.1 for carbon and ±0.15 for nitrogen, which is the uncertainty provided by the laboratory of analysis.

The potential food sources (*Food groups*), with their respective composition of macronutrients (*Food fractions:* bulk, protein, and energy) were grouped in four categories: terrestrial faunal-TF, contributing proteins and lipids; marine faunal-MF, providing proteins and lipids; and C_3 plants, and C_4 plants, both contributing carbohydrates and proteins (Fernandes, et al., 2014; Fernandes et al., 2015; Pezo-Lanfranco et al., 2022). The mean isotope values from each food group are shown in Table 1.

For $\delta^{13}C$, the diet-collagen fractionation factor was set at 4.8 ± 0.5 ‰, and at 5.5 ± 0.5 ‰ for $\delta^{15}N$ (Fernandes, 2016). The weighted values

Table 1
Mean $\delta^{13}C$ and $\delta^{15}N$ values (‰) for plants and animals of the Peruvian Central Coast.

		$\delta^{13}C$		$\delta^{15}N$	
Food category	N	$\bar{x}$	σ	$\bar{x}$	σ
C_4 plants (maize)	16	−11.3	1.4	7.3	3.0
CAM plants*	2	−10.8	0.2	3.8	0.4
C_3 plants	38	−25.7	2.1	5.3	3.2
Marine fauna	34	−11.9	2.1	13.2	3.0
Terrestrial fauna	17	−17.5	3.2	9.0	3.1

* Not used in models.

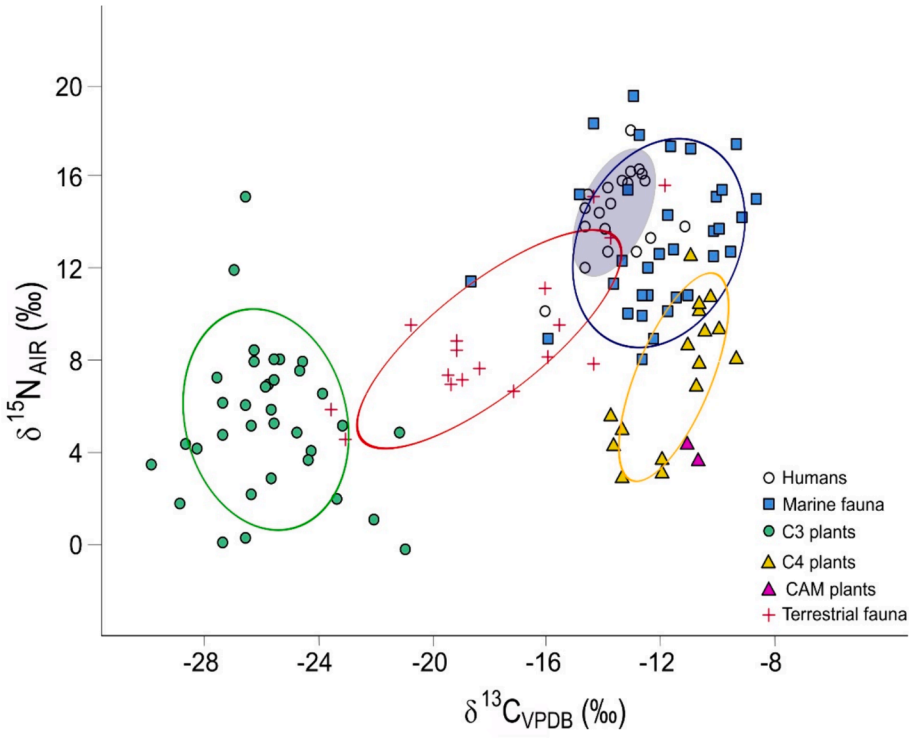

Fig. 2. Scatterplots of $\delta^{13}C$ and $\delta^{15}N$ values and Standard Ellipse Areas for edible plants and fauna of the Peruvian Central Coast discriminated by food groups. Each Standard Ellipse Area represents an estimated 68 % of the population (rKin package, Albeke, 2017; Robinson, 2022). The shaded ellipse corresponds to the H20 individuals studied herein.

of each fraction of macronutrients (lipids, carbohydrates, and proteins) were set based on previously published parameters (Fernandes, et al., 2014; Fernandes et al., 2015; Colonese et al., 2020; Pezo-Lanfranco et al., 2022). For collagen, the carbon of the protein and energy routed to the total collagen was established at 74 ± 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 combinatory effect, we applied a "concentration-dependent" model (Fernandes, et al., 2014; Fernandes et al., 2015).

The isotopic composition of each nutritional fraction (protein, carbohydrates, and lipids) was derived from the mean values of $\delta^{13}C$ and $\delta^{15}N$ using the following fractionation factors: −2‰ ($\Delta^{13}C_{protein\text{-}collagen}$), −8‰ ($\Delta^{13}C_{lipids\text{-}collagen}$), and + 2 ‰ ($\Delta^{15}N_{protein\text{-}collagen}$) for terrestrial mammals, and −1 ‰ ($\Delta^{13}C_{protein\text{-}collagen}$), −7‰ ($\Delta^{13}C_{lipids\text{-}collagen}$), and + 2 ‰ ($\Delta^{15}N_{protein\text{-}collagen}$) for marine animals. For plants, the offsets were − 2 ‰ ($\Delta^{13}C_{bulk\text{-}protein}$) and +0.5 ‰ ($\Delta^{13}C_{bulk\text{-}lipids}$), while for the $\delta^{15}N$ value of plant protein, the known value of $\delta^{15}N$ recorded for the plant was assumed. The carbon weight (*concentration*) of each food fraction (protein and energy) from each food group was calculated according to its macronutrient composition (see details in Fernandes et al., 2015).

Finally, the dietary estimates were parametrized by a physiological, conservative, and acceptable range of protein consumption stipulated between 5 % and 45 % of the total calories (Fernandes et al., 2014). Based on the archaeological inventories, we assumed more marine protein than terrestrial protein in the model. These inputs were charged as "priors".

4. Results

4.1. $\delta^{13}C$ and $\delta^{15}N$ values according to sex and life-stage

Among the 49 teeth analyzed (11 infant stages, 25 childhood stages and 13 adolescent stages), 20 had sufficient dentine collagen for $\delta^{13}C$ and $\delta^{15}N$ analysis. These samples corresponded to 5 infant stages, 10 childhood stages and 5 adolescent stages. The recovered collagen had atomic compositions typical of well-preserved archaeological collagen (Table 2, Supporting Information 1: ST3b), namely with C:N ratios ($\bar{x}$ = 3.33 ± 0.16), and weights of carbon (wt%C 42.0 ± 3.7 %) and nitrogen (wt%N 14.8 ± 1.5 %) within conventional values (2.9–3.6 [DeNiro, 1985]; 26 %–44 % and 11 %–16 % [Van Klinken, 1999], respectively).

The $\delta^{13}C$ and $\delta^{15}N$ values from virtually all individuals fall within the marine ellipse, reflecting the intake of marine proteins along with C_4 plants (maize) and to a lesser extent terrestrial proteins (Table 3 and Fig. 2). Although the small sample size prevented reliable statistical comparisons among groups, the data sorted by age suggest the gradual transition from a plant-based diet in infants to a diet with more marine protein in adolescents (Fig 3).

In addition, $\delta^{15}N$ values among male and female infants differ, with males showing comparatively higher values than females (Tables 2 and 3). In children and adolescents, sex-based differences are unclear, with the females showing slightly higher $\delta^{15}N$ values. However, other sample issues (i.e., greater number of females compared to males) could be introducing bias into our interpretations.

4.2. Dietary reconstruction with BISMMs

The trends observed in the ellipses are consistent with the BISMMs estimates (Tables 4 and 5, Fig. 4, and Supporting Information ST4 for raw individual results). The preadults of H20 at the beginning of the Middle Horizon widely relied on C_4 plants (maize?), which provides 40 − 45 % of calories in the diet. The infants relied on a combination of C_4 and C_3 but consume more C_3 than the older groups with minimal consumption of marine protein. The children show decreasing consumption of C_3 and increased marine protein, whereas adolescents receive 45 % of calories from C_4 plants, 41 % from C_3 plants, and 10 − 15 % from marine fauna. This diet, which was possibly like the adult diet of H20, shows a

Table 2
Sample information along with atomic and stable isotope values from well-preserved dentine collagen of Huaca 20 individuals (n = 20).

ID	Sex	Age-range in years	Tooth (segment sampled)	Tissue age-rangein years (median age)	Life-stage†	%C	%N	C/N*	$\delta^{13}C$	$\delta^{15}N$
T 25	F	±25	Lower LPm1 (root)	6.0 – 15.0 (10.5)	Child	43.68	16.76	3.0	−12.7	12.7
T 27	F	Adult	Upper LM1 (root)	3.5 – 9.5 (6.5)	Child	39.84	15.57	3.0	−12.2	13.3
T 41	M	±33	Lower LM1 (crown)	0.4 – 3.5 (1.95)	Infant	32.95	11.37	3.4	−14.0	14.4
T 45	M	Adult	Upper RI2 (crown)	0.8 – 5.0 (2.9)	Infant	43.33	14.83	3.4	−14.5	14.6
T 48	M	Adult	Lower RM2 (root)	8.0 – 16.5 (12.25)	Adolescent	36.78	12.29	3.5	−12.4	15.8
T 55	F?	Adult	Lower RM2 (root)	8.0 – 16.5 (12.25)	Adolescent	44.84	17.39	3.0	−13.0	15.7
T 83	M	±30	Upper RI1 (root)	4.5 – 11.0 (7.25)	Child	44.92	15.79	3.3	−13.6	14.8
T 84	M	±33	Lower Canine ($^1/_3$ root)	5.0 – 8.0 (6.5)	Child	42.88	14.91	3.4	−12.9	18.0
T 85	M	±35	Lower Pm (root)	5.5 – 14.0 (9.75)	Child	37.65	13.85	3.2	−14.5	12.0
T 94	F	±35	Upper RM1 ($^1/_3$ root)	3.5 – 5.0 (4.25)	Infant	44.37	14.80	3.5	−11.0	13.8
T 101-A	F?	Adult	Lower RM1 (root)	3.5 – 9.5 (6.5)	Child	45.57	15.63	3.4	−12.5	16.1
T 101-B	F	Adult	Lower RPm2 ($^2/_3$ root)	6.5 – 12.0 (9.25)	Child	45.20	15.78	3.3	−13.8	13.7
T 102	F	30 – 45	Upper Pm1 (root)	6.0 – 15.0 (10.5)	Child	43.20	15.09	3.3	−12.9	16.2
T 107	F	21 – 24	Upper M3 (crown and $^1/_3$ root)	8.5 – 15.0 (16.75)	Adolescent	39.70	13.80	3.4	−12.6	16.3
T 114	F?	Adult	Upper Pm (root)	6.0 – 15.0 (10.5)	Child	45.17	15.41	3.4	−14.5	13.8
T 117	F?	Adult	Lower RPm1(root)	5.5 – 14.0 (9.75)	Child	45.37	16.08	3.3	−13.7	15.5
T 126	F	Adult	Upper Pm (root)	6.0 – 15.0 (10.5)	Child	43.25	14.65	3.4	−14.4	15.2
T 152	F	25 – 35	Lower M2 (crown)	2.5 – 8.0 (5.25)	Infant	35.83	11.99	3.5	−15.9	10.1
T 211	M	20 – 25	Upper LM3 (crown)	8.5 – 14.0 (11.25)	Adolescent	42.79	14.50	3.4	−13.2	15.8
T 383	F	25 – 35	Lower RM1 (crown)	0.4 – 3.5 (1.95)	Infant	43.37	14.96	3.4	−13.7	12.7

Sex: M=male, F=female, Und = undetermined;?=Probable; Adult: adult individual without age-range estimation. **n.a:** collagen not available or insufficient for measurement. *Individuals with underlined C:N ratios were excluded from the analysis. †Individuals were classified in life-stages by the calculation of the median age of the age range in the following categories: Infant: < 6 years; Child: 6 – 11 years; Adolescent: >11 – 20 years.

Table 3
Mean isotopic values by sex and life-stage in Huaca 20.

Sex		n	min.	max.	$\bar{x}$	σ
Male	$\delta^{13}C$	7	−14.5	−12.4	−13.6	0.8
	$\delta^{15}N$	7	12.0	18.0	15.0	1.8
Female	$\delta^{13}C$	13	−15.9	−11.0	−13.3	1.2
	$\delta^{15}N$	13	10.1	16.3	14.2	1.8
Life-stage		n	min.	max.	$\bar{x}$	σ
Infant	$\delta^{13}C$	5	−15.9	−11.0	−13.8	1.8
	$\delta^{15}N$	5	10.1	14.6	13.1	1.8
Child	$\delta^{13}C$	11	−14.5	−12.2	−13.4	0.8
	$\delta^{15}N$	11	12.0	18.0	14.7	1.8
Adolescent	$\delta^{13}C$	4	−13.2	−12.4	−12.8	0.4
	$\delta^{15}N$	4	15.7	16.3	15.9	0.3
Pooled individuals	$\delta^{13}C$	20	−15.9	−11.0	−13.4	1.1
	$\delta^{15}N$	20	10.1	18.0	14.5	1.8

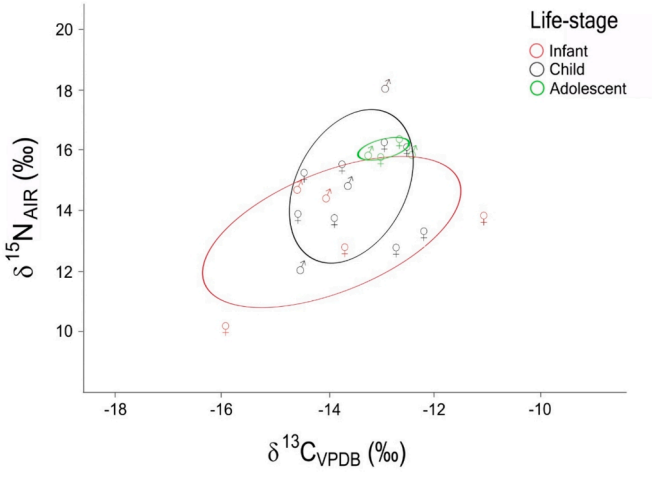

Fig. 3. Dentine $\delta^{13}C$ and $\delta^{15}N$ values and Standard Ellipse Areas of H20 individuals classified by sex (♂= male; ♀= female) with overlapped and Standard Ellipse Areas by life-stage. Each Standard Ellipse Area of isotopic niches represent an estimated 68% of the population.

marine contribution lower than expected for a population living relatively close to the sea in caloric terms, although there are some exceptions (e.g., T84 consumed 30 % of calories from marine protein). The consumption of terrestrial animal protein was negligible in the entire population, although slightly higher in older preadults.

In sum, the caloric contribution of C_4 plants is around 42 % in all the life-stages with little fluctuation. Calories from C_3 plants fluctuate from 52 % in infants, to 46 % in children, and 40 % in adolescents. Marine protein consumption was variable in children and much lower in infants (<25 %). Marine food provides not more than 12 % of total calories in adolescents, but, on the other hand, this equals around 48 % of the total protein, without sex-based differences (Table 5).

5. Discussion

5.1. Approximation to the diet in Huaca 20

Our stable isotopes and BISMMs analyses offer glimpses of subsistence systems in H20 at the Maranga Complex, one of the main settlements of the Lima culture at the beginning of the Middle Horizon. The test of our hypotheses in light of the results and the available (bio) archaeological evidence enables one approximation for the diet and productive strategies for the site and region. Further research is needed, however, as we currently do not have adult isotope values.

We have hypothesized that the diet at H20 was mainly based on agricultural products. A diet composed largely of plants for caloric intake would support such a hypothesis. In addition, our results support the hypothesis that maize was the main plant component in the diet, especially in older preadults. Nevertheless, it was not the only carbohydrate source, as C_3 plant contribution is also relatively high, complemented with marine protein in modest amounts. We also hypothesized that the diet of preadult individuals from H20 varies according to age and sex, in possible correspondence with their social position and economic activities. This hypothesis is partially confirmed, with our results suggesting that older preadults had greater access to protein. The relationship between dietary regimes, gender, and social position requires clarification.

Regarding the first hypothesis, the regional record of C_3 plants includes tubers, legumes, cucurbits and fruits, whereas among the C_4 plants, the only domesticated crop is maize. There is no evidence of

Table 4
Estimates of dietary calories contribution of each food group in preadults from Huaca 20*.

ID	Sex	Life-stage	C_4 plants		C_3 plants		Terrestrial protein		Marine protein	
			$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
T 383	F	Infant	0.45	0.06	0.52	0.06	0.01	0.01	0.02	0.01
T 41	M	Infant	0.39	0.06	0.53	0.05	0.02	0.02	0.06	0.03
T 45	M	Infant	0.36	0.07	0.55	0.07	0.03	0.02	0.06	0.03
T 94	F	Infant	0.62	0.07	0.33	0.07	0.02	0.01	0.04	0.02
T 152	F	Infant	0.34	0.05	0.65	0.05	0.00	0.00	0.01	0.01
T 27	F	Child	0.58	0.05	0.38	0.05	0.01	0.01	0.03	0.01
T 84	M	Child	0.22	0.12	0.33	0.13	0.16	0.10	0.30	0.10
T 101-A	F	Child	0.42	0.09	0.41	0.08	0.05	0.05	0.12	0.07
T 83	M	Child	0.42	0.07	0.49	0.07	0.03	0.02	0.06	0.03
T 101-B	F	Child	0.43	0.06	0.52	0.06	0.02	0.01	0.04	0.02
T 85	M	Child	0.41	0.06	0.56	0.06	0.01	0.01	0.02	0.01
T 117	F	Child	0.40	0.07	0.48	0.06	0.04	0.03	0.08	0.03
T 25	F	Child	0.55	0.07	0.43	0.07	0.01	0.01	0.02	0.01
T 114	F	Child	0.39	0.07	0.55	0.07	0.02	0.01	0.04	0.02
T 126	F	Child	0.37	0.06	0.51	0.06	0.04	0.03	0.08	0.02
T 102	F	Child	0.39	0.09	0.41	0.07	0.07	0.05	0.14	0.07
T 211	M	Adolescent	0.41	0.09	0.43	0.07	0.05	0.04	0.11	0.06
T 55	F	Adolescent	0.42	0.07	0.44	0.06	0.04	0.04	0.10	0.05
T 48	M	Adolescent	0.46	0.10	0.38	0.09	0.06	0.05	0.11	0.07
T 107	F	Adolescent	0.39	0.12	0.37	0.08	0.08	0.07	0.16	0.10

*Estimates based on FRUITS v. 2.1.1 using the collagen $\delta^{13}C$ and $\delta^{15}N$ values of individuals (Fernandes et al., 2015). Foods (%): estimates of dietary carbon/calories contribution of each food group, expressed as relative contributions (summing to 100 %) with an associated 1σ uncertainty (Fernandes et al., 2015: Table 5).

Table 5
Estimates of dietary protein contribution of each food group in preadults from Huaca 20*

ID	Sex	Life-stage	C_4 plants		C_3 plants		Terrestrial protein		Marine protein	
			$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
T 383	F	Infant	0.41	0.11	0.39	0.10	0.03	0.02	0.17	0.07
T 41	M	Infant	0.28	0.11	0.31	0.09	0.07	0.05	0.34	0.10
T 45	M	Infant	0.26	0.10	0.33	0.08	0.07	0.05	0.34	0.08
T 94	F	Infant	0.50	0.11	0.21	0.08	0.05	0.03	0.25	0.08
T 152	F	Infant	0.28	0.11	0.64	0.11	0.01	0.01	0.06	0.04
T 27	F	Child	0.49	0.11	0.27	0.09	0.04	0.03	0.20	0.07
T 84	M	Child	0.07	0.06	0.07	0.05	0.17	0.08	0.69	0.09
T 101-A	F	Child	0.24	0.10	0.15	0.07	0.10	0.06	0.50	0.11
T 83	M	Child	0.31	0.10	0.26	0.08	0.08	0.05	0.36	0.09
T 101-B	F	Child	0.35	0.11	0.35	0.09	0.05	0.04	0.25	0.08
T 85	M	Child	0.37	0.11	0.47	0.09	0.03	0.02	0.13	0.06
T 117	F	Child	0.25	0.10	0.24	0.08	0.09	0.05	0.42	0.09
T 25	F	Child	0.50	0.12	0.31	0.10	0.03	0.02	0.15	0.06
T 114	F	Child	0.31	0.12	0.38	0.09	0.05	0.03	0.26	0.08
T 126	F	Child	0.25	0.09	0.27	0.08	0.09	0.05	0.39	0.09
T 102	F	Child	0.21	0.10	0.16	0.07	0.12	0.07	0.52	0.11
T 211	M	Adolescent	0.24	0.11	0.18	0.07	0.11	0.06	0.46	0.10
T 55	F	Adolescent	0.26	0.10	0.20	0.08	0.10	0.06	0.45	0.09
T 48	M	Adolescent	0.26	0.10	0.16	0.07	0.10	0.07	0.47	0.11
T 107	F	Adolescent	0.20	0.11	0.14	0.07	0.12	0.07	0.54	0.12

*Estimates based on FRUITS v. 2.1.1. Since the only source of dietary nitrogen is assumed to be protein, the estimate for ^{15}N indicates the relative calorie protein contribution of each food group (Fernandes et al., 2015).

amaranth, another C_4 plant, at this latitude for this period (León, 2014). CAM plants such as cacti, although possibly consumed, were excluded from the analysis because of their low caloric contribution and debatable value as a food staple.

Maize was of particular importance from the Formative Period (i.e., Tablada de Lurin, 200 BCE−200 CE: Gerdau-Radonić et al., 2015) to the Late Intermediate Period (i.e., Armatambo and Rinconada Alta, 900 − 1470 CE: Marsteller 2015). In Armatambo (lower valley) and Rinconada Alta (middle valley), diets were based on marine protein and mixed C_3-C_4 sources with a slightly greater contribution of C_4 (maize), which was the most important staple along with other C_3 plants such as peanut (*Arachys hypogea*) and some tubers like *jíquima* (*Pachyrrizus tuberosus*) and *achira* (*Canna indica*).

On the other hand, the H20 diet was not strictly plant based. Fish from the region had mean $\delta^{15}N$ values around 13 ‰, with expected values for marine consumers of >16 ‰, whereas terrestrial fauna had $\delta^{13}C$ values around −18 ‰ and $\delta^{15}N$ < 12 ‰ (Pezo-Lanfranco and Colonese, 2024). Thus, the main source of dietary protein in H20 was marine, although possibly from low trophic level species. This is supported by the presence of small fish, such as anchovy and sardines, and mollusks in the record (Mauricio, 2012). Overall, terrestrial protein intake was low. Although archaeological remains from this period in the valley include terrestrial fauna, such as birds, cervids, rodents (*Cavia porcellus*), and domesticated camelids *Lama* sp. (Mauricio, 2012; Vargas, 2015), our results suggest that they were only intermittently consumed in H20, as reported for other sites in the Andes (Pezo-Lanfranco & Colonese, 20024).

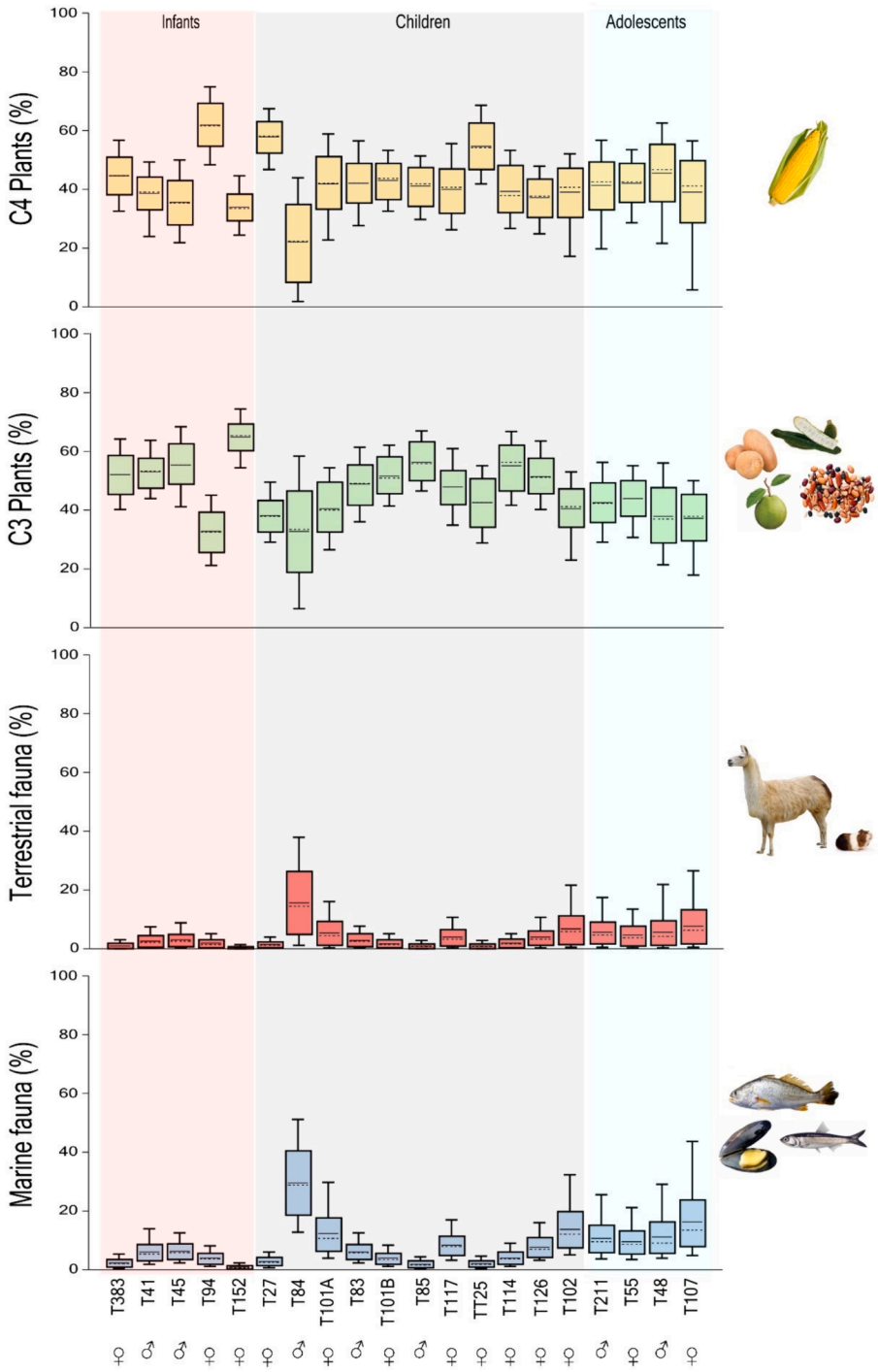

Fig. 4. Preadult dietary caloric estimations of food sources from Huaca 20 individuals ordered by age. The boxes represent a 68 % confidence interval and the whiskers a 95 % confidence interval. The horizontal discontinuous line indicates the median and the continuous line indicates the mean. The sex of each individual is indicated by ♂= male and ♀= female.

5.2. *Diet through life-stages in H20*

Our results offer valuable insights into how preadults were fed and integrated into the economic life of the community. The teeth of sexed adults potentially provide information about parental investment and gender-specific nutritional differences between preadult males and females. There is a trend to a wider diet in females, even though considerable overlap is also observed.

Due to the combinatory effect of several layers of dentine representing different ages in the roots, and sample restrictions, it was not possible to detect exclusively breast-fed individuals (theoretically, with $\delta^{15}N$ values $> 2 - 4$ ‰ compared to adult females). Nevertheless, the values of some individuals suggest they were consuming a supplementary diet, which included both breast milk and solid or semi-solid food (Katzenberg et al., 1996; Humphrey, 2014).

Three H20 infants (T353, T41, T45) show $\delta^{15}N$ values lower than expected for exclusive breastfeeders or consumers of weaning diets (Tsutaya and Yoneda, 2015). Several reasons, not mutually exclusive, could explain this picture: a) these outliers missed the breastfeeding period; b) they were weaned early and fed with weaning foods of low-

trophic level; c) their nurses repassed low $\delta^{15}N$ values to the infant because they did not consume marine resources; or finally, d) as their $\delta^{15}N$ values come from M1 crowns, these unexpected low $\delta^{15}N$ values could be related to the presence of tertiary dentine linked to dental wear, and thus containing a "more adult" value. The other two infants possibly represent post weaning diets. For instance, T94 (female, approximately 4 years old) showed the highest maize consumption of the entire sample but had little marine protein ($\delta^{15}N<14$ ‰, 25 % of total protein consumed), while T152 is possibly an example of a weaned individual with a terrestrial C_3 diet that showed a value consistent with an anabolic physiological event. Among the H20 infants, males consumed slightly more marine protein than females. In all the cases, we must consider that isotope values come from "healthy survivors" that reached adulthood, so their infant data may be low in $\delta^{15}N$ because they were well-nourished individuals (Feuillatre et al., 2022).

Although a more variable diet among females and more protein provision in males could suggest parental investment focused on male offspring, compatible with resources-rich environments and low inter-individual competition (Cronk, 2007; Higginson and Aarssen, 2011), in H20, protein was provided in lower amounts to all infants, and started to be consumed in greater amounts only by children and adolescents. Thus, age seems to be a more important factor than sex in dietary shifts.

A clearer trend in H20 is related to weaning strategies and baby care. To avoid issues with the infectious potential of the solid adult diet in infants, mothers sometimes delay the introduction of weaning food. This scenario is known as the "weaning dilemma" because this delay can lead to malnutrition after the first 6–8 months (Katzenberg et al., 1996). This consumption of carbohydrate-based infant food and the delay of protein introduction could explain the low indices of pathologies observed in bioarcheological analyses (Cleary, 2019), suggesting an infant population less exposed to potential pathogens in marine foods (Patrucco et al., 1983; Huss et al., 2000).

The type, proportion and value of food sources provided to children differs with culture and environment (Tsutaya et al., 2014; Tsutaya, 2017). In H20, infant diets were largely carbohydrate-based. The mixed C_3-C_4 diet observed in infants at H20 suggests that they likely consumed gruels, porridges, or soups. The C_3 plants of the Rimac Valley at that time included tubers, like sweet potato, *jíquima* and achira, and quinoa, in addition to the starchy varieties of maize found during this period (Grobman et al., 1961, 2012; Bonavia, 2008), all of which would have been appropriate for preparing soft-textured meals.

Maize may have been used as a first ranking weaning food, however, an alternate explanation for the elevated proportions of C_4 in infants is that they were receiving the C_4 values through breastmilk from mothers who consumed high amounts of maize. It remains unclear if infants and children at H20 consumed *chicha* (a maize beverage, fermented or unfermented). Gruel or *chicha* made of maize are common elements of weaning diets in modern Peru (Antúnez de Mayolo, 1981; Bonavia, 2008; León, 2013).

Some scholars suggest that with the adoption of agriculture, domesticated species allowed the production of infant food that, in many cases, improved infant nutrition and survival, leading to population growth through an early weaning age and shorter birth intervals (Buikstra et al., 1986; Crown and Wills, 1995). This is a plausible hypothesis in H20.

After weaning, children can be introduced to an adult diet or a special "transitional" diet which differs from adults (Dupras and Tocheri, 2007; Humphrey, 2014; Pezo-Lanfranco et al., 2018). Post-weaning diets of farmers show significantly larger proportions of lower trophic level items than adults, mainly plants (Tsutaya, 2017). Yet, in H20, children show an increase of marine protein, which can be interpreted as the lack of a transitional diet and could be related to the introduction of the children into productive activities, or self-acquisition in older preadult life-stages (Eerkens and Bartelink, 2013; Tsutaya, 2017). Among the faunal protein sources, the easiest to capture would be mollusks and some intertidal fishes.

The individual with the highest $\delta^{15}N$ value was a male child (T84). Although we cannot define if the high $\delta^{15}N$ is an effect of physiological stress, among the individuals with the lowest $\delta^{15}N$ values, most are female. In H20, most males display $\delta^{15}N$ values > 14 ‰, whereas half of the females show values < 14 ‰. Malnutrition has been argued to explain the elevated $\delta^{15}N$ values due to nitrogen recycling during growth (Feuillatre et al., 2022). In this case, the tissues sampled were forming over several years, and considering that this child survived until adulthood, muscle catabolism over an extended period seems less plausible than marine protein consumption as an explanation for this high $\delta^{15}N$ value.

The evidence of sex-based division of labor for adults in funerary contexts is limited to the presence fishhooks for males and spindle whorls mostly for females. It is not clear within our sample set whether men were the fishers and consuming more marine resources on average than women, thus leading to younger boys learning to become fishermen and consuming more fish than girls. What can be seen is that males and females consumed marine resources in variable amounts. Similarly, if women were more involved with agriculture or preparing food within the domicile, in agreement with their roles at that age, perhaps younger girls were helping their mothers in the kitchen. Such training for later gender roles might expose children to more of one food over another.

The adolescent diet, which can be representative of the adult diet, contains more maize and, in general, more marine protein and from higher trophic levels. Other isotopic studies have documented a more varied diet for females, and a more homogeneous and higher protein diet for males in several societies, often relating these to differences in workloads, energy demands, social prescriptions, or access during daily life (Reitsema and Vercellotti, 2012; Eerkens and Bartelink, 2013; Pezo-Lanfranco et al., 2018). In H20 the proportion of protein is similar among most adolescents and cannot be related to status, gender or economic activity. The effects of physiological factors linked to puberty (i.e., a significantly higher than required protein intake), could be a plausible alternative explanation for these high trophic level $\delta^{15}N$ values (O'Connel et al., 2012; Feuillatre et al., 2022).

Some comparative studies have stated that dentine is a more reliable tissue than bone for subadult dietary reconstruction because it is less exposed to the effects of physiological stress during infant and child growth (Beaumont et al., 2018). Dentine sequential sampling is the ideal method to assess breastfeeding, weaning and post-weaning diets in past populations (Beaumont et al., 2018; Tsutaya and Yoneda 2015; Czermak et al., 2020). The method used herein, although less precise, is an effective alternative for evaluating dietary shifts over lifetime, particularly in cases where tissue preservation is an issue. This method, nevertheless, faces some potential limitations such as issues with the attribution of age to dental segments, and isotopic equifinality. Dentine layers in the dental crown and roots come from different periods, thus the method is ambiguous about weaning/postweaning age assessment because a sample's values correspond to a mean of various mixed layers from different periods. Further, tooth eruption and development are not co-dependent processes and are parametrized by several nutritional and physiological factors (Feuillatre et al., 2022). For instance, stunted children can have delayed eruption, but tooth formation is unaffected (Elamin and Liversidge, 2013). With no specific charts for tooth development yet postulated for Andean populations, inferences about the age of dental sections are challenging. Although some methods on tooth eruption/development can be applied across populations (Ubelaker, 1999; Gaither, 2004), some populations, including H20 (Vega, 2009), have shown earlier eruption chronologies compared to international standards (AlQhatani et al., 2010). Finally, isotopic equifinality can occur when different combinations of food contributions result in the same isotopic values, and this should be considered a latent confounding factor in paleodietary reconstructions.

CRediT authorship contribution statement

Luis Pezo-Lanfranco: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rafael Vega-Centeno Sara-LaFosse:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Gustavo Aliaga-Rodríguez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation. **Pau Comes Bordas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **André Carlo Colonese:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors are grateful to Krista McGrath for the revision of the final draft, José Marti for their valuable collaboration during the sampling work, and the *Dirección de Infraestructura* and *Dirección de Asuntos Culturales* of the Pontificia Universidad Católica del Perú, Peru. The research has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie Action project PACHAMAMA, Grant Agreement N° 101062179 (LPL); and the ERC Consolidator project TRADITION, Grant Agreement N° 817911 (ACC). This work contributes to the "ICTA-UAB María de Maeztu" Program for Units of Excellence of the Ministry of Science and Innovation, Spain (CEX2019-000940-M). This work also contributes to EarlyFoods (Evolution and impact of early food production systems), funded by the Agència de Gestió d'Ajuts Universitaris i de Recerca de Catalunya, Spain (SGR-Cat-2021, 00527). The funders had no role in the study design, data collection and analysis, the decision to publish, or the preparation of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104723.

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