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ORIGINAL PAPER

# Diet and food strategies in a southern al-Andalusian urban environment during Caliphal period, Écija, Sevilla

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## Abstract

The Iberian medieval period is unique in European history due to the widespread socio-cultural changes that took place after the arrival of Arabs, Berbers and Islam in 711 AD. Recently, isotopic research has been insightful on dietary shifts, status, resource availability and the impact of environment. However, there is no published isotopic research exploring these factors in southern Iberian populations, and as the history of this area differs to the northern regions, this leaves a significant lacuna in our knowledge. This research fills this gap via isotopic analysis of human (*n* = 66) and faunal (*n* = 13) samples from the 9th to the 13th century Écija, a town renowned for high temperatures and salinity. Stable carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N) isotopes were assessed from rib collagen, while carbon ($\delta^{13}$C) values were derived from enamel apatite. Human diet is consistent with $C_3$ plant consumption with a very minor contribution of $C_4$ plants, an interesting feature considering the suitability of Écija to $C_4$ cereal production. $\delta^{15}$N values vary among adults, which may suggest variable animal protein consumption or isotopic variation within animal species due to differences in foddering. Consideration of $\delta^{13}$C collagen and apatite values together may indicate sugarcane consumption, while moderate $\delta^{15}$N values do not suggest a strong aridity or salinity effect. Comparison with other Iberian groups shows similarities relating to time and location rather than by religion, although more multi-isotopic studies combined with zooarchaeology and botany may reveal subtle differences unobservable in carbon and nitrogen collagen studies alone.

**Keywords** Al-Andalus · Islamic archaeology · Isotope · Medieval · Apatite · Collagen

## Introduction

This research aims to explore the dietary habits and resources of the inhabitants of Écija, southern Iberia, during the Medieval period (9th to 13th centuries). There has been intense archaeological and historical interest in the lives of the Medieval inhabitants of the Iberian Peninsula (e.g. Alexander et al. 2015; Boone 2009; Carvajal Lopez 2013; Garcia-Garcia 2016; Glick 1999; Imamuddin 1981; Inskip 2016; Menocal 2002; al-Oumaoui et al. 2004), due to the significant and widespread socio-cultural changes that took place after Arab and Berber expansions reached the region in AD 711. Islam became the dominant faith, and the reintroduction and dissemination of knowledge, via the translation of texts once lost to the Latin west, proved to be critical to the later European Renaissance (Menocal 2002). One of the most important and debated issues at this time is the so-called “agricultural” or “green revolution”, which considers the importance of changes in water management and technology and the (re)introduction of certain crops to the region (see Martín Civantos 2016; Watson 1974; but also Decker 2009). It is thought that there was greater cultivation of non-indigenous

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crops, such as sugarcane, millet, sorghum, pomegranate and dates, in the region (Watson 1974). Crop cycling changed, and a better agricultural output was achieved (Reilly 1993; Glick 1995). It is likely that there were shifts in animal husbandry practices (Grau-Sologestoa 2015) and a pork taboo emerged (see Garcia-Garcia 2017; Morales Muñiz et al. 2011).

Recently, stable isotope analyses, which have proved invaluable in improving understanding of dietary practices and environments in the past (Katzenberg and Waters-Rist in press; Larsen 2015), have been used to assess dietary and environmental changes during this time period. For example, interesting diversity in Iberian isotope values recorded in archaeological skeletons potentially relates to geography, religion and social status (Alexander et al. 2015; Mundee 2009; Quiros Castillo et al. 2013). However, at present, most isotopic research focuses on sites from northern and central Iberia (e.g. Alexander et al. 2015; Lopez-Costas 2012; Passalacqua and MacKinnon, 2015; Prevedorou et al. 2010; Quiros Castillo et al. 2013; Mundee 2009) or the Islands (Fuller et al. 2010; Garcia et al. 2004; Nehlich et al. 2012), leaving much of the south unknown.

The environment and history of Iberia, with the south being part of the Islamic world for far longer, are highly diverse. Accordingly, the lack of isotopic data for the south leaves a large gap in our regional knowledge, resulting in an incomplete picture of the complexity that existed in Medieval Iberia. An isotopic analysis of diet for a southern Iberian population would permit analyses of sociocultural change and identity. In addition, while religious and cultural factors are important in the selection of food preferences, it cannot be ignored that availability of resources could play a key role in what people ate in the past. Supplies could arrive by trade (and may not have been available for all the population) or could have been grown locally; in this case, the climate can influence the type and amount of produced food. The 9th century AD is considered as the beginning of a climate anomaly known as the Medieval Warm Period (MWP) that lasted until the 14th century (Broecker 2001; Martinez-Cortizas et al. 1999). During MWP, climate was warm and arid in the Mediterranean and southern areas of the Iberian Peninsula, but warm and humid in the Atlantic region (Moreno et al. 2012). Therefore, the exploration of diet via stable isotopes for individuals who lived in Southern Iberia during the MWP may also help us understand the role of climate in the availability of resources, specifically the use of crops dependent on warm temperatures, such as the $C_4$ plants including sugarcane and millet. Mapping what is happening on a regional level could highlight important information about what was happening on a much wider scale during this critical time period.

Accordingly, a multi-isotope study assessing stable carbon ($\delta^{13}C$) from collagen and enamel apatite and nitrogen ($\delta^{15}N$) from sixty six humans and thirteen animals from the Medieval site of Écija in southcentral Iberia is used to meet the three aims of this paper. First, we aim to reconstruct the staple food resources consumed by the inhabitants of Écija. Second, we aim to use evidence of diet to infer aspects of the physical as well as socio-political environment in which the Écija people lived. Third, and most broadly, this research will contribute the first isotopic evidence of diet for this region, thereby improving our understanding of Medieval Iberian dietary variability across the entire peninsula. This will be achieved through the analysis of skeletal material from the medieval Islamic cemetery in Écija, Seville province, Spain.

## Historic background

Écija is a small urban area in the South-centre of al-Andalus, renowned for its agricultural richness (arid-warm temperatures and water supply from the Genil river). The city, known as Astiya in the Islamic period, is situated in the Genil river valley between the Subbetico zone to the north and Guadalquivir to the south. Today, the area is well-known for its high salinity (Fernandez et al. 2002). The "Altiplano de Écija", surrounding the city, is an area traditionally dedicated to livestock and agriculture where numerous salt water lagoons are present. Écija is located between three major cities, all which were extant in the Medieval period. This includes Seville to the west (≈ 85 km), Córdoba to the north east (≈ 50 km) and Granada to the south east (≈ 170 km) (see Fig. 1). This positioning has meant that Écija has long been an important trading and strategic point from the Roman period onwards (Valencia Rodriguez 1988).

According to historic sources, Écija was captured in AD 711 by Tariq b. Ziyad, the year of Arab and Berber expansion into the region (Chalmeta 1994). While it is thought that Arab groups, especially Damascens, settled in the region, a number of sources suggest that the town contained a significant number of local converts to Islam (Aillet 2010; Melville and Ubaydli 1992). The surrounding countryside was settled by Berbers (Valencia Rodriguez 1988). During the medieval period, Écija was a multi-cultural/religious city: Muslims, Muwallads (converted Christians), Mozarabs (i.e. Christians living under Islamic rule) and Jews, with a clear Islamic influence in terms of economy, culture and society (Garcia Baena 2006). This diversity was maintained while Écija was the regional capital of the Cora Istiyya, which presented some economic independence (Valencia Rodriguez 1988). The city itself was medium to large in size with estimates of approximately 18,000 inhabitants by the 12th century (Fernandez Ugalde 2005). From the 11th century until its conquest in 1240 AD, it is believed that diversity decreased, and by the 11th century, Écija lost its independence to Carmona and eventually Seville (Guichard and Soravia, 2005). Based on this information, Islamic Écija is the perfect example of an urban population whose economy was based on agriculture and livestock, with different socioeconomic phases (ibid) making it ideal for study.

**Fig. 1** Map locating Écija in comparison to Seville, Granada and Córdoba

## Medieval diet in al-Andalus and Écija

In general, historic sources and zooarchaeology suggest that Medieval Iberian populations had a diet consisting of cereals and meats (Morales Muñiz et al. 2011; Salas-Salvado et al. 2006). Écija is recorded as an important town for cereal production (Imamuddin 1981), especially wheat and barley (García-Baena 2006). A number of new cereals, such as sorghum, are thought to have been introduced into Iberia during the Medieval period (Glick 1999). Millets were probably introduced during the Early or Late Bronze Age (López-Costas et al. 2015) and became extremely popular in some regions, such as northwestern Iberia (López-Costas and Müldner 2016). It is possible that these were grown in the Écija region (García Baena 2006), as the climate is particularly suited to their cultivation. Sugarcane may have arrived first to southern and eastern Iberia during the 9th century for family consumption as is mentioned in the 10th century agricultural Calendar of Cordoba (Sato 2015) and it may have become an export product only several centuries later (Perez Vidal 1973). In other Islamic lands, the relationship between sugar consumption and Ramadan is recorded in poetry by the 9th century, potentially making it a desirable plant (Sato 2015). While there are strong doubts surrounding the possibility to detect the consumption of sugarcane from isotopic ratios from bone collagen, because the protein content is low, a reconstruction combining collagen and bioapatite, as employed here, could reveal if this product was an important part of the diet (O’Leary 1988). A number of Islamic texts also mention the use of legumes including chickpeas, lentils and beans for making bread (García Sánchez 1995). Olives, honey, raisins, meat, almonds, chestnut and saffron are also reported to be important products of Écija (García Baena 2006; Melville and Ubaydli 1992) and were viewed as nutritious (Salas-Salvado et al. 2006). Dairy products were likely an important part of diet, as well as fruit and vegetables, which grew in abundance in the region. Salt was also exploited in the nearby region (García-Dils de la Vega et al. 2009).

Historical sources suggest that cattle (beef) and especially sheep (mutton) were the main sources of meat for Islamic inhabitants (Morales Muñiz et al. 2011), and Écija is thought to be no exception (García Baena 2006). This trend appears to be borne out by recent zooarchaeological research in nearby Córdoba and Granada (Garcia-Garcia 2016, 2017) and Islamic Portugal (Grau-Sologestoa 2015). This research has hinted at the formation of structured caprine herding system from the 10th century (see discussions in Garcia-Garcia 2017). Salas-Salvado et al. (2006) suggest that meat consumption by ordinary people was probably limited to special occasions, and infrequent on the tables of the poor. Zooarchaeological studies show a decline in the consumption of pig with the advent of the Islamic period (Garcia-Garcia 2016; Morales Muñiz et al. 2011); however, pig remains occasionally appear at Islamic sites even if in low amounts, which may relate to necessity, status, presence of Christian groups or indifference (see Garcia-Garcia 2016). Accordingly, consumption of pork should not be ruled out. In nearby Granada and Córdoba, a high quantity of rabbit remains was identified (Garcia-Garcia 2016, 2017). With wild animals, their discovery fits with notions that some people, especially of high status, may have hunted and eaten game. This could also include deer and wild birds. As Écija is on a river, river resources may be consumed. However, there is little data on fresh water exploitation in the Islamic period in Écija. The river had silted up after the Roman period; however, some regulations for fishing the Genil exist from 15th to 17th centuries AD (Hernández Iñigo 1997).

## Stable isotopes and dietary reconstruction

As the analysis of stable isotopes for dietary reconstruction is well-established and widely utilised in bioarchaeology, and the mechanisms underlying stable isotope fractionation within and between tissues and ecosystems have been outlined in extensive detail elsewhere (Ambrose et al. 1997; DeNiro and Epstein 1978, 1981; Katzenberg and Waters-Rist in press; Lee-Thorp and van der Merwe 1987; van der Merwe and Vogel 1978), only a brief explanation will be provided. Nitrogen isotope ratios ($\delta^{15}$N) in the protein component of bone, collagen, predominately reflect the trophic level of the proteins that individuals consume (Bocherens and Drukker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984). This allows researchers to reconstruct the types of animal and/or plant proteins that were dietary staples. Marine ecosystems have more steps in the foodweb and thus reach higher trophic levels with higher $\delta^{15}$N values than terrestrial ecosystems (Schoeninger and DeNiro 1984); in many freshwater ecosystems, the same is true, with top trophic level species having high $\delta^{15}$N values (e.g. Katzenberg et al. 2010). Breastfeeding infants will exhibit $\delta^{15}$N values 2–4‰ higher than their mother, which decline during the weaning process (Fuller et al. 2006). Stable carbon isotope ratios in bone collagen ($\delta^{13}C_{coll}$) are useful in distinguishing between plants that use different photosynthetic pathways ($C_3$ vs. $C_4$ plants) (DeNiro and Epstein 1978; Vogel and van de Merwe 1977). $C_3$ plants include rice, wheat and barley while $C_4$ plants include maize, sugarcane, sorghum and millet. Stable carbon isotopes are also used to identify the consumption of marine, and sometimes freshwater foods, as aquatic plants utilise different carbon sources (i.e. mostly dissolved carbonates) than terrestrial plants (i.e. atmospheric $CO_2$) thereby passing along a distinctive $\delta^{13}$C ratio to species higher in the trophic chain (Chisholm et al. 1983; Schoeninger and DeNiro 1984).

In contrast to bone, which continuously remodels throughout life and provides a record of diet for the last ten or more years of life in adults (Hedges et al. 2007), the isotopic analyses of enamel from different teeth reveals values that were obtained for different ages in subadulthood. Enamel only forms in infancy and childhood and thereafter does not undergo remodelling. The enamel of deciduous molars begins forming in utero and is complete prior to the first postnatal year (Liversidge and Molleson 2004). The permanent first molar enamel begins formation around birth and is completed by the age of about three years; the enamel of the permanent second molar begins formation around three years and is completed by six to seven years of age; and finally, third molar enamel begins formation from eight to nine years being completed by eleven to twelve years of age (Reid and Dean 2006; derived from Northern European population data).

The stable carbon isotope ratio of tooth enamel apatite ($\delta^{13}C_{ap}$) is a better reflection of whole diet, including protein, carbohydrate and fat, than $\delta^{13}$C from collagen which is derived more heavily from the protein component of diet (Ambrose and Norr 1993; Krueger and Sullivan 1984; Lee-Thorp et al. 1989; Tieszen and Fagre (1993). The comparison of $\delta^{13}$C ratios from protein vs. apatite components of biological tissues has been successful in more effectively discerning among dietary behaviours.

## Materials

### Human samples

The cemetery in the El Salon region of Écija (location 37°32′ 27.89 N, 5°04′45.49 W) is thought to have been the major burial place for the city (Garcia Baena 2006). It was mainly used between the 9th and the 13th centuries AD, with the majority of burials dating to the Caliphal period (10th–11th centuries) (Romo Salas n.d.). By 2004, over 4500 individuals had been excavated and are now stored at the Municipal Museum in Écija. These skeletons were distributed over seven layers in three different areas of the square. Here, the seven periods of burial have been divided into Early (7th–3rd phases) and Late (1st–2nd phases) cemetery layers. Men, women, and children of all ages are represented in all layers. The funerary rite was clearly Islamic in nature, with nearly all individuals buried on their right side with their face in the direction of Mecca (Inskip 2016; Romo Salas n.d.). While most individuals were in simple graves, there was some variation in grave structure, and it is believed that the burials represent a cross-section of society (Romo Salas n.d.). The macroscopic preservation of bone is generally good, but overcrowding resulted in some intercutting of burials. For the purpose of this study, only individuals from single burials were used. A total of 61 human rib samples from 61 different individuals were used for $\delta^{13}C_{coll}$ and $\delta^{15}N$ analysis. Fifty teeth from 47 individuals were sampled for $\delta^{13}C_{ap}$ analysis (M1 = 12, M2 = 12 and M3 = 26). In total, 66 different individuals were analysed. Age and sex were previously estimated from Inskip (2013) and the unpublished osteological report (Romo Salas n.d.). In the current study, individuals were classed as adult at approximately 16 years or over. Young adults were between 16 and 35 years, middle adults were between 35 and 50 years, and old adults were 50 years+. Within the subadult category, the majority of individuals are between 2 and 6 years, with only two individuals between 12 and 16 years. Infants were less than 2 years. Table 1 outlines the demographic composition of the sample; Table 2 outlines the number of individuals in each phase.

**Table 1** Number of adults, males, females and subadults used in this study, and sample numbers for collagen and enamel extraction

| Group | C and N collagen | C and O apatite | Total individuals analysed* |
|---|---|---|---|
| Males | 20 | 21 | 24 |
| Females | 15 | 12 | 17 |
| Unsexed adult | 3 | 4 | 6 |
| Subadult | 12 | 9 | 14 |
| Infant | 5 | 1 | 5 |
| Total | 55 | 47$^{+}$ | 66 |

* Note, some individuals were not analysed for both collagen and apatite due to preservation or completeness

**Table 2** Number of adults, males, females and subadults used according to period

| Period | Female | Male | Unsexed adult | Subadult | Infant | Total |
|---|---|---|---|---|---|---|
| Early | 6 | 12 | 1 | 5 | 3 | 27 |
| Late | 5 | 7 | 0 | 4 | 1 | 17 |
| Unknown | 6 | 5 | 5 | 5 | 1 | 22 |
| Total | 17 | 24 | 6 | 14 | 5 | 66 |

### Faunal material

Due to the lack of previous comparable isotopic studies for this region, a faunal isotopic baseline was created. We collected 13 bones from animals excavated from different archaeological layers of the cemetery at Écija. Unfortunately, we do not know what layers the animal bones originate from as this was not recorded during excavation. Bone samples from five caprine (sheep or goat), six cattle, one pig and one rabbit were analysed. All specimens were adult. It was not possible to determine if the pig or rabbit were domestic or wild specimens. The presence of cut marks together with the settlement context suggests that they were butchered and consumed.

### Collagen extraction and mass spectrometry

We sampled rib bone fragments rather than sawing from intact ribs. This was done to restrict the amount of destructive sampling and to preserve intact elements for future research. Collagen extraction and purification took place at the departments of Archaeology at Leiden University and University of Reading using two different protocols. Fifty-four human samples were analysed using a modified Sealy method (Sealy 1986; Sealy 2010). All rib samples were placed in a bath of distilled water ($dH_2O$) and cleaned ultrasonically. Samples were demineralized in a 1% solution of HCl, changed every 24–38 h until complete. All samples were rinsed with $dH_20$ prior to the NaOH bath. They were gelatinized by the HCl step prior to transferring them into the NaOH bath. Samples were considered sufficiently demineralized upon the formation of a milky-white pseudomorph which could be easily pierced with a sterilised needle. Intact collagen pseudomorphs were then transferred to a 0.125 M solution of sodium hydroxide (NaOH) for 20 h to remove humic contaminants and then rinsed and soaked in $dH_2O$ until a neutral pH (7) was achieved. Samples were then freeze-dried. At Vrije Universiteit, Amsterdam, collagen samples were combusted using a Thermo-Scientific Flash 2000 organic elemental analyser with the resultant gases introduced into the Delta V plus isotope ratio mass spectrometer via a continuous flow (Conflo) inlet. USGS40, USG41, USG42 and glycine were used as reference standards.

All faunal samples and samples from seven human adults were processed following the method described by Longin (1971) with modifications recommended by Collins and Galley (1998), according to the protocol described in Britton et al. (2008). The NaOH step was not applied. Carbon and nitrogen stable isotope ratios were measured in duplicate on a Europa 20-20 isotope ratio mass spectrometer coupled to a Sercon elemental analyser at the University of Reading. Isotopic values are reported as δ values in per thousand (‰). Stable carbon isotope values are reported relative to the Vienna PeeDee Belemnite (VPDB) marine limestone standard, and nitrogen isotope values are reported relative to the international nitrogen standard, air.

Precision of stable carbon and nitrogen isotope measurements, determined via repeated analysis of an internal laboratory standard, is ± 0.2‰ for both methods. No significant differences were found due to the extraction method (*U* test between human adult samples $n = 28$ and 7: M-W test $U = 78.000$, $p = 0.43$ for $\delta^{13}C$; $U = 83.000$, $p = 0.56$ for $\delta^{15}N$). Accordingly, all samples are considered together.

The quality (preservation; degree of contamination) of the isotopic data garnered from each bone collagen sample was measured according to disciplinary standards: atomic C/N ratio, collagen yield, and percentage C and N by weight (Ambrose 1990; Ambrose and Norr 1993; Bocherens et al. 1991; DeNiro 1985; DeNiro and Weiner 1988; Schoeinger 1989; van Klinken 1999) (see Table 3).

## Dental samples

**Enamel apatite and mass spectrometry** Standard enamel apatite extraction and preparation procedures were based on Lee-Thorp et al. (1997). All dental samples were cleaned using a diamond-tipped dremel, and the underlying enamel was sampled in bulk. Bulk sampling involved harvesting enamel evenly across the entire surface of the tooth, from just above the CEJ to just below the occlusal surface. Approximately 10 mg of powdered enamel apatite was collected from each tooth. Faunal samples were prepared similarly. Powdered samples were loaded into marked 2 ml microcentrifuge tubes and soaked in a 0.1 M commercial liquid bleach solution[1] for 45 min, in order to eliminate organic and biogenic contaminants. Samples were then centrifuged. The bleach solution was then removed from the enamel precipitate using a pipette, and the sample was rinsed with $dH_20$. A total of three rinse-centrifuge cycles were conducted. The enamel was then reacted in 0.1 M of acetic acid ($CH_3COOH$) for 15 min to remove soluble diagenetic carbonates. Samples were rinse-centrifuged for another three times with distilled water and then freeze-dried.

Carbon isotope values were measured using a Finnigan DeltaPlus isotope ratio mass spectrometer. Pre-treated enamel samples (0.19–2.1 mg) were transferred into sterilised mass spectrometry tubes and reacted with phosphoric acid ($H_3PO_4$) at 72 °C to produce gaseous carbon dioxide. The resultant gas was isolated on a Gasbench II universal automated interface. As a measure of reproducibility and quality control, IAEA-CO1 was used as a reference standard (see Table 3). Standard deviations of repeated measurements of laboratory standards were 0.16‰ for $\delta^{13}C$.

## Statistical analysis

Statistical analyses were conducted using IBM SPSS statistical software (version 22.0 for Windows 8). A Shapiro–Wilk's test of normality and a visual inspection of the associated histograms, normal Q–Q plots and box–plots, indicate that both the human bone collagen $\delta^{13}C$ ($W(55) = 0.887$, $p = < 0.0001$) and $\delta^{15}N$ ($W(55) = 0.931$, $p = < 0.004$) datasets and the enamel apatite $\delta^{13}C$ ($W(52) = 0.815$, $p = < 0.00001$) datasets are non-normally distributed. A Levene's test for homogeneity of variance verified equality of variances in the $\delta^{13}C$ ($F(2, 52) = 0.273$, $p = 0.762$) and $\delta^{15}N$ ($F(2, 52) = 0.584$, $p = 0.561$) human bone collagen and the $\delta^{13}C$ ($F(2, 49) = 0.562$, $p = 0.574$) enamel apatite dataset. Given the relatively small sample sizes and the non-normal distribution of the data, non-parametric statistical analyses were employed. The Wilcoxon–Mann–Whitney *U* test was used for the comparison of the two samples, and a Kruskal–Wallis *H* test was used for comparison of three or more groups (i.e. between tooth types). A Dunn's pairwise comparison test was used as a post-hoc test, whenever a Kruskal–Wallis *H* test was rejected. Significance level ($\alpha$) was set at 0.05.

# Results

Stable isotope values for all samples are presented in Table 3 and are visually depicted in Fig. 2a.

## Quality control

Of the original 61 human rib samples, six failed for poor quality of the extracted collagen (no collagen, C/N out of range). The remaining fifty-five human and thirteen faunal collagen samples had C/N ratios between 2.9 and 3.6 which is considered good-quality collagen (Van Klinken 1999). Collagen yields were generally low and ranged between 10.1 and 0.1. The arid environment in Écija is probably the reason for the low recovery rates of collagen in the bone. The vast majority of the samples (63/67) had percent nitrogen (wt% N) in collagen values above 10%

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[1] 8% sodium hypochlorite in distilled water.

**Table 3** Sample numbers, cemetery period, sex, age, tooth type and stable isotope data for all samples

| Sample code | Period | Sex | Age | Tooth | ‰ $\delta^{13}C_{app}$ | Element | ‰ $\delta^{13}C_{coll}$ | ‰ $\delta^{15}N$ | Atomic C/N | %N wt | %C wt | Collagen yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11931 | Un | ? | ? | LM2 | − 6.54 | – | – | – | – | – | – | – |
| 1869 | E | N/A | Infant | – | – | Rib | − 18.9 | 12.9 | 2.9 | 13.8 | 41.2 | 5.2 |
| 2170 | E | N/A | Infant | – | – | Rib | − 18.4 | 12.6 | 3 | 14.5 | 35 | 7.8 |
| 2527 | Un | N/A | Infant | – | – | Rib | − 19.3 | 9.5 | 3.3 | 14.3 | 38.8 | 4.3 |
| 6447 | E | N/A | Infant | – | – | Rib | − 19.6 | 12.9 | 3.2 | 13.6 | 40 | 3.6 |
| 11916 | E | N/A | Infant | LM2 | − 10.3 | Rib | − 19.2 | 9.2 | 3.2 | 13.8 | 37.3 | 5.6 |
| 2030 | Un | N/A | Subadult | UM1 | − 11.7 | Rib | − 18.6 | 13.6 | 3.2 | 14.1 | 40.3 | 2.9 |
| 2772 | Un | N/A | Subadult | – | – | Rib | − 18.7 | 11.6 | 3.4 | 13.9 | 39.9 | 2 |
| 4421 | L | N/A | Subadult | UM1 | − 11.6 | Rib | − 19.6 | 12.2 | 3.3 | 13.7 | 41.1 | 2.1 |
| 4574 | L | N/A | Subadult | LM1 | − 10.5 | Rib | − 19.3 | 11.6 | 3.3 | 12.4 | 37.1 | 3.5 |
| 4776 | L | N/A | Subadult | LM1 | − 11.4 | Rib | − 18.8 | 9.8 | 3.2 | 13.8 | 39.5 | 4 |
| 5255 | E | N/A | Subadult | LM1 | − 10.6 | – | – | – | – | – | – | – |
| 5462 | L | N/A | Subadult | – | – | Rib | − 12 | 9.2 | 3.4 | 12 | 29 | 5.3 |
| 5601 | E | N/A | Subadult | – | – | Rib | − 18.4 | 9.9 | 3.5 | 13.5 | 39 | 2.5 |
| 10206 | E | N/A | Subadult | – | – | Rib | − 19.4 | 9.9 | 3.4 | 11.2 | 28 | 4 |
| 11321 | E | N/A | Subadult | LM1 | − 10.7 | Rib | − 19.4 | 9 | 3.2 | 12.4 | 35.1 | 4.4 |
| 11989 | Un | N/A | Subadult | – | – | Rib | − 18.2 | 12 | 3.3 | 13.7 | 39.1 | 2.9 |
| 12063 | Un | N/A | Subadult | LM3 | − 6.4 | – | – | – | – | – | – | – |
| 12283 | E | N/A | Subadult | UM1 | − 9.4 | Rib | − 21.3 | 13.4 | 3.4 | 14.2 | 42.5 | 2 |
| 532 | L | M | Young adult | LM2 | − 11 | Rib | − 19.6 | 11.6 | 3.2 | 12.9 | 39.5 | 6.2 |
| 532 | L | M | Young adult | LM3 | − 11.6 | – | – | – | – | – | – | |
| 655 | E | M | Young adult | LM3 | − 11.8 | – | – | – | – | – | – | |
| 3801 | L | F | Young adult | LM2 | − 11.3 | Rib | − 19.3 | 9.4 | 3.2 | 14.4 | 41.2 | 4.7 |
| 3801 | L | F | Young adult | LM3 | − 11.1 | – | – | – | – | – | – | – |
| *5230 | Un | F | Young adult | – | – | Rib | − 19.1 | 9.7 | 3.3 | 14.7 | 41.2 | 2.4 |
| 5757 | E | M | Young adult | UM1 | − 12 | – | – | – | – | – | – | – |
| 5920 | L | M | Young adult | M1 | − 12.1 | Rib | − 18.7 | 9.2 | 3.3 | 13.8 | 37.3 | 7.8 |
| 6795 | E | M | Young adult | M3 | − 12.4 | Rib | − 19.3 | 9.7 | 3.2 | 14.2 | 38.5 | 2 |
| 6801 | E | M | Young adult | M2 | − 9.7 | Rib | − 19.2 | 9.3 | 3.3 | 13.1 | 37.5 | 4.6 |
| 7578 | E | F | Young adult | – | – | Rib | − 19.2 | 11.9 | 3.3 | 14.6 | 33.5 | 5.6 |
| 7968 | E | M | Young adult | LM3 | − 8.2 | Rib | − 18.1 | 11.6 | 3.2 | 14.2 | 40.6 | 4.8 |
| 9027 | E | M | Young adult | LM3 | − 11.6 | Rib | − 19 | 10.1 | 3.2 | 14.1 | 40.2 | 4.5 |
| 10021 | E | F | Young adult | LM3 | − 11.2 | Rib | − 19.4 | 9.8 | 3.2 | 11.8 | 33.5 | 2 |
| 10027 | E | F | Young adult | LM3 | − 11.4 | Rib | − 19.2 | 8.4 | 3.2 | 14.1 | 38.2 | 4.5 |
| 12271 | E | M | Young adult | UM3 | − 11.4 | Rib | − 18.7 | 10.5 | 3.2 | 14.4 | 39.2 | 4.6 |
| 12601 | L | F | Young adult | LM3 | − 10.4 | Rib | − 19.3 | 9.7 | 3.2 | 13.7 | 39.1 | 4.8 |
| 5093 | E | M | Young adult | – | – | Rib | − 18.9 | 11.4 | 3.2 | 14.1 | 38.2 | 2.9 |
| 11681 | E | M | Young adult | UM3 | − 11.3 | Rib | − 19.2 | 9.9 | 3.2 | 13.8 | 37.6 | 7.8 |
| 11752 | E | F | Young adult | LM3 | − 11.8 | Rib | − 19.1 | 9.6 | 3.2 | 15.9 | 39.7 | 10.1 |
| 2817 | Un | M | Middle adult | UM3 | − 11.9 | Rib | − 18.9 | 9.4 | 3.3 | 12 | 34.1 | 2.5 |
| 3697 | L | M | Middle adult | LM3 | − 11.4 | Rib | − 18.6 | 10.8 | 3.2 | 13.5 | 39.2 | 7.2 |
| 6810 | Un | F | Middle adult | – | – | Rib | − 19.1 | 11.1 | 3.3 | 13.8 | 41.5 | 4.8 |
| *6825 | Un | F | Middle adult | – | – | Rib | − 19.4 | 8.9 | 3.2 | 15.3 | 42.5 | 2.2 |
| 9163 | E | M | Middle adult | LM3 | − 12 | – | – | – | – | – | – | – |
| 10326 | E | M | Middle adult | UM1 | − 13.1 | Rib | − 19.1 | 8 | 3.2 | 14 | 40 | 2.1 |
| 11083 | E | M | Middle adult | LM2 | − 10.6 | – | – | – | – | – | – | – |
| 11083 | E | M | Middle adult | LM3 | − 11.7 | – | – | – | – | – | – | – |

**Table 3** (continued)

| Sample code | Period | Sex | Age | Tooth | ‰ $\delta^{13}C_{app}$ | Element | ‰ $\delta^{13}C_{coll}$ | ‰ $\delta^{15}N$ | Atomic C/N | %N wt | %C wt | Collagen yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *11309 | Un | N/A | Middle adult | – | – | Rib | − 18.9 | 10.1 | 3.2 | 16.1 | 44.6 | 7.3 |
| 11837 | E | ? | Middle adult | UM3 | − 11.2 | – | – | – | – | – | – | – |
| 11873 | E | F | Middle adult | LM3 | − 11.3 | Rib | − 19.3 | 9.3 | 3.2 | 14.3 | 36.9 | 10.1 |
| 12872 | L | F | Middle adult | UM1 | − 11.6 | Rib | − 19.4 | 11.2 | 3.3 | 11.9 | 31.5 | 5.3 |
| 492 | L | M | Middle adult | LM2 | − 11.4 | Rib | − 19.7 | 9.4 | 3.4 | 12.2 | 36.4 | N/A |
| 5902 | E | M | Middle adult | M3 | − 12.1 | Rib | − 18.7 | 11.6 | 3.4 | 13.8 | 37.3 | 2.1 |
| 10957 | L | F | Middle adult | LM3 | − 11.1 | Rib | − 18.8 | 9.5 | 3.3 | 14 | 38 | 4.2 |
| 11333 | E | M | Middle adult | UM1 | − 10.1 | Rib | − 19.1 | 11.8 | 3.3 | 12.5 | 33.1 | 2.5 |
| 12286 | E | N/A | Middle adult | UM2 | − 12.3 | Rib | − 19.3 | 9.9 | 3.2 | 15.8 | 41.3 | 6.1 |
| 12895 | L | M | Middle adult | LM3 | − 13 | Rib | − 19.3 | 9.6 | 3.3 | 11.7 | 35 | 2.8 |
| 509 | L | M | Old adult | LM3 | − 10.9 | Rib | − 19.2 | 9.5 | 3.2 | 13.6 | 38.8 | 5.6 |
| 2561 | Un | U | Old adult | UM2 | − 12 | – | – | – | – | – | – | |
| *3094 | Un | M | Old adult | – | – | Rib | − 18.7 | 9.8 | 3.3 | 10.3 | 28.8 | 2.5 |
| 3863 | L | F | Old adult | LM2 | − 12.1 | Rib | − 18.8 | 8.7 | 3.2 | 14.4 | 41.2 | 2.5 |
| 3863 | L | F | Old adult | LM3 | − 11.9 | – | – | – | – | – | – | – |
| 4238 | L | N/A | Old adult | – | – | Rib | − 18.5 | 13.1 | 3.3 | 13.7 | 39.1 | 1.4 |
| 6855 | E | M | Old adult | – | – | Rib | − 19.1 | 8.4 | 3.3 | 13.7 | 37 | N/A |
| 9247 | E | F | Old adult | LM3 | − 11.8 | Rib | − 18.6 | 10.6 | 3.3 | 13.9 | 39.6 | 5.3 |
| *11461 | Un | F | Old adult | – | – | Rib | − 19.1 | 9.9 | 3.2 | 15.4 | 43 | 2.5 |
| *11550 | Un | N/A | Old adult | – | – | Rib | − 19.2 | 10.1 | 3.2 | 15.5 | 42.7 | 4.5 |
| 12677 | L | M | Old adult | LM2 | − 11.9 | Rib | − 19.3 | 10.3 | 3.2 | 12.2 | 32.5 | 4.4 |
| 12577 | L | F | Adult | LM2 | − 13 | – | – | – | – | – | – | – |
| 12577 | L | F | Adult | LM3 | − 12.3 | – | – | – | – | – | – | – |
| *Cattle-967 | Un | N/A | Adult | – | – | Tarsal | − 18.8 | 5.8 | 3.4 | 14.7 | 42.6 | 1.3 |
| *Cattle-966 | Un | N/A | Adult | – | – | Jaw | − 19.8 | 9.3 | 3.5 | 4 | 11.8 | 1.4 |
| *Cattle-964 | Un | N/A | Adult | – | – | Jaw | − 18.7 | 8.8 | 3.2 | 14.9 | 41.3 | 3.9 |
| *Cattle-961 | Un | N/A | Adult | – | – | Tibia | − 20 | 5.7 | 3.3 | 14.3 | 40.1 | 1.7 |
| *Cattle-958 | Un | N/A | Adult | – | – | Vertebra | − 17.8 | 7.3 | 3.4 | 11.5 | 33.5 | 1.3 |
| Cattle | Un | N/A | Adult | – | – | Jaw | − 20.6 | 4.1 | 3.2 | 11.6 | 34.9 | 12.4 |
| *Caprine-965 | Un | N/A | Adult | – | – | Tarsal | − 21 | 6.8 | 3.3 | 12.7 | 36 | 2.4 |
| *Caprine-969 | Un | N/A | Adult | – | – | Tarsal | − 19.6 | 6.6 | 3.2 | 14.3 | 39.9 | 7.1 |
| *Caprine-959 | Un | N/A | Adult | – | – | Tarsal | − 20.9 | 9.6 | 3.3 | 15.7 | 44.2 | 15.7 |
| *Caprine-968 | Un | N/A | Adult | – | – | Metacarpal | − 20.1 | 8.3 | 3.2 | 15.6 | 42.5 | 7.4 |
| *Caprine-963 | Un | N/A | Adult | – | – | Tarsal | − 19.6 | 6.6 | 3.2 | 14.6 | 40.6 | 3.4 |
| *Pig-962 | Un | N/A | Adult | – | – | Humerus | − 19.3 | 8.1 | 3.3 | 14.7 | 41.1 | 2.5 |
| *Rabbit-960 | Un | N/A | Adult | – | – | Coxal | − 22.5 | 4.7 | 3.4 | 14.3 | 41.3 | 5.4 |
| IAEA-CO1 | N/A | N/A | N/A | N/A | − 2.61 | Standard | N/A | N/A | N/A | N/A | N/A | N/A |

* Samples analysed at University of Reading

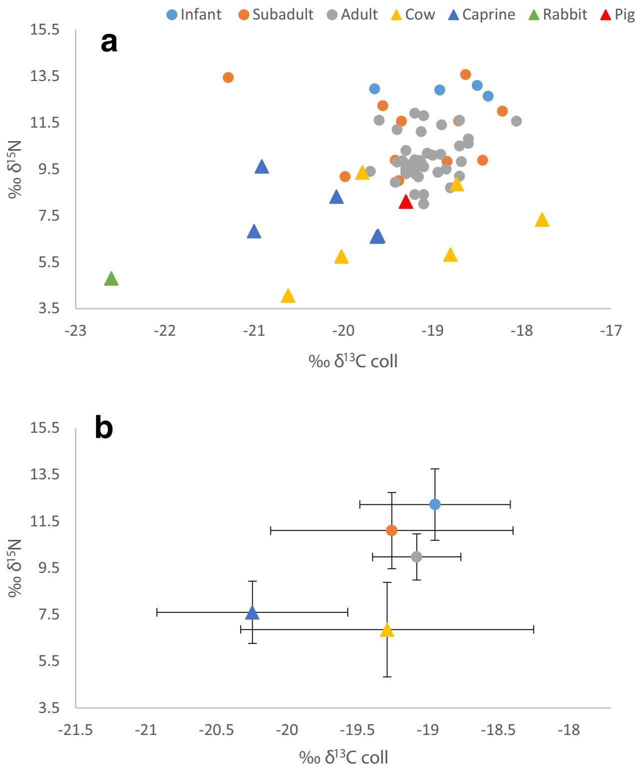


**Fig. 2** **a** Collagen isotopic value for fauna, adults, subadults and infants in the Écija sample with mean values for fauna. **b** Average values and standard deviations for infants, subadults, adults, cows and caprines

and below 16% (see Table 3). Four samples showed low %N, the first two 8.1% and the others 4.0%; however, since their C/N ratio was acceptable and isotopic results were in line with similar samples, both samples were retained (see Table 3).

Unlike bone, enamel apatite is less likely to be affected by post-mortem mineral exchange or diagenesis (Kohn et al. 1999; Lee-Thorp 2002), and there are no standard quality control measures.

## Carbon and nitrogen isotopic signatures from faunal samples

A summary of the isotope values for the Écija faunal data is presented in Table 4.

The rabbit has the lowest $\delta^{13}C_{coll}$ and second lowest $\delta^{15}N$ values, − 22.6 and 4.8‰, respectively. When medium–large herbivores, cattle and caprine, are considered together, both present a moderate to high range of variation, 3.2‰ for $\delta^{13}C_{coll}$ (− 21‰, − 17.8‰) and 3.9‰ $\delta^{15}N$ (5.7‰, 9.6‰). The average caprine $\delta^{13}C_{coll}$ and $\delta^{15}N$ values are − 20.3 and 7.6‰, while that of the cattle are − 19.2 and 6.9‰ for $\delta^{13}C_{coll}$ and $\delta^{15}N$, respectively. The isotopic variability in $\delta^{13}C_{coll}$ is wider for cattle than for caprine (2.2 and 1.4‰, respectively; Table 4 and Fig. 2b) and slightly wider for $\delta^{15}N$ (3.6 and 3.0‰, respectively; Table 4 and Fig. 2b). Although, in general, the cattle displayed less negative $\delta^{13}C_{coll}$ and higher $\delta^{15}N$ than caprine, these differences are not statistically significant (U test between cattle and caprine: M-W test $U = 4.000$, $p = 0.09$ for $\delta^{13}C_{coll}$; $U = 14.000$, $p = 0.84$ for $\delta^{15}N$); however, the sample size tested is small. The results for the pig sample fall into the range of analysed large herbivore data.

## Carbon and nitrogen isotopic signatures from bone collagen in human samples

The human data have an average of − 19.1 ± 0.5‰ for $\delta^{13}C_{coll}$ and 10.4 ± 1.4‰ for $\delta^{15}N$ ($n = 55$). The sample of 12,283 constitutes an outlier in $\delta^{13}C_{coll}$ (see Fig. 2), since the value (− 21.3‰) is more than 1.3‰ lower than the next minimum human value and 2.2‰ lower than the human average. The outlier is not included in the statistics. Not considering the outlier, the human sample range is 1.9‰ (− 20.2 to − 18.1‰) for $\delta^{13}C_{coll}$ (see Fig. 2b). The results for $\delta^{15}N$ display continuous variation from 8.0 to 13.6‰, a wide range of 5.6‰. However, excluding infants and subadults, the range is reduced to 2.9‰ (8.0 to 11.9‰) (see Fig. 2b).

The $\delta^{13}C_{coll}$ of human bone collagen is not significantly different from the cattle samples ($n = 6$) ($U = 142.50$, $p = 0.60$); however, human and cattle differ significantly in their $\delta^{15}N$ values ($U = 15$, $p = < 0.001$). Human samples are significantly different from caprine ($n = 5$) samples in both $\delta^{13}C_{coll}$ ($U = 11.00$, $p < 0.001$) and $\delta^{15}N$ ($U = 20.00$, $p < 0.001$). The offset between the human and the large herbivore (cattle and caprine) average is 0.6‰ for $\delta^{13}C_{coll}$ and 2.8‰ for $\delta^{15}N$, which can be considered small, although, for $\delta^{15}N$ approximately 3.0‰ can reflect a trophic level difference (O'Connell et al. 2012). The human average and the rabbit value also show a large isotopic shift, 3.5‰ for $\delta^{13}C_{coll}$ and 5.6‰ for $\delta^{15}N$.

Prior to testing whether differences exist between demographic groups, variation in isotope values between

**Table 4** Statistical summary of the $\delta^{13}C_{coll}$ and $\delta^{15}N$ results for terrestrial animals from Écija

| Animal | *n* | $\delta^{13}C_{coll}$ (‰) | SD | Range | $\delta^{15}N$(‰) | SD | Range |
|---|---|---|---|---|---|---|---|
| Rabbit | 1 | − 22.6 | – | – | 4.8 | – | – |
| Cattle | 6 | − 19.2 | 1.1 | − 20.6 to − 17.8 | 6.9 | 2.2 | 4.1 to 9.4 |
| Caprine | 5 | − 20.3 | 0.7 | − 21.0 to − 19.6 | 7.6 | 1.3 | 6.6 to 9.6 |
| Pig | 1 | − 19.3 | – | – | 8.1 | – | – |

individuals assigned to either the Early period (7–3 phases, $n = 25$) or Late period (1–2 phases, $n = 17$) of cemetery use was tested: No significant differences exist (samples with phase information $n = 42$; M-W test $U = 162.000$, $p = 0.19$ for $\delta^{13}C_{coll}$; $U = 201.000$, $p = 0.77$ for $\delta^{15}N$). No differences were found when the sexes were considered independently (males Early/Late periods $n = 11/7$; M-W test $U = 22.000$, $p = 0.15$ for $\delta^{13}C_{coll}$; $U = 33.500$, $p = 0.66$ for $\delta^{15}N$); (females Early/Late periods $n = 6/5$; M-W test $U = 13.500$, $p = 0.79$ for $\delta^{13}C_{coll}$; $U = 13.000$, $p = 0.79$ for $\delta^{15}N$). The numbers of infants and subadults were insufficient to test between groups; however, visual inspection of the data presented no obvious differences. Since the analysed samples show no isotopic differences according to period, the whole sample is studied as a single group. Table 3 outlines isotopic results for each individual analysed. The descriptive statistics for all three isotopes taken from the human samples are presented in Table 5.

## Adults versus subadults

It should be noted that combined infants and subadults show significant differences to the adults in nitrogen values (infants and subadults without outlier/adults $n = 17/38$; $U = 424.500$, $p = 0.02$ for $\delta^{15}N$) but not in carbon (M-W test $U = 312.500$, $p = 0.87$ for $\delta^{13}C_{coll}$) (see Fig. 2a,b). A Kruskal–Wallis $H$ test assessed for significant variation in stable carbon and nitrogen isotope values between infants (< 2 years) ($n = 5$), subadults (between 2 and 6 years) ($n = 12$) and adults ($n = 38$). A significant difference was only observed for nitrogen isotope values ($\delta^{13}C_{coll} = \chi^2$ (2) = 0.720, $p = 0.700$; $\delta^{15}N = \chi^2$ (2) = 10.00, $p = 0.007$). A Dunn's pairwise comparison of $\delta^{15}N$ by age indicates that infants vary significantly from adults ($D = -2.70$, $p = 0.010$) but do not vary significantly with subadults at the 0.05 level ($D = -2.06$, $p = 0.060$). Subadults do not vary significantly from the adult population ($D = 1.07$, $p = 0.430$).

**Table 5** Descriptive statistics for stable carbon and nitrogen isotope values from collagen and stable carbon from enamel in the Écija collection

| Isotope (‰) | Group | N | Max | Min | Mean | SD |
|---|---|---|---|---|---|---|
| $\delta^{15}N$ | Infants | 5 | 13.1 | 9.5 | 12.2 | 1.5 |
| | Subadults | 12 | 13.6 | 9.0 | 10.9 | 1.6 |
| | All adult | 38 | 11.9 | 8.0 | 10.0 | 1.0 |
| | Female | 15 | 11.9 | 8.4 | 9.8 | 1.0 |
| | Male | 20 | 11.8 | 8.0 | 10.1 | 1.1 |
| | ?Adults | 3 | 10.2 | 9.9 | 10.1 | 0.2 |
| $\delta^{13}C_{coll}$ | Infants | 5 | − 18.3 | − 19.6 | − 18.9 | 0.5 |
| | Subadults | 12 | − 18.2 | − 21.3 | − 19.2 | 0.8 |
| | All adult | 38 | − 18.1 | − 19.7 | − 19.1 | 0.3 |
| | Female | 15 | − 18.6 | − 19.4 | − 19.2 | 0.2 |
| | Male | 20 | − 18.1 | − 19.7 | − 19.0 | 0.4 |
| | ?Adults | 3 | − 18.9 | − 19.3 | − 19.1 | 0.2 |
| $\delta^{13}C_{ap}$ | Infant | 1 | – | – | − 11.9 | – |
| | Subadults | 8 | − 6.4 | − 11.7 | − 10.3 | 1.7 |
| | All adult | 37 | − 8.2 | − 13.1 | − 11.5 | 0.9 |
| | Female | 12 | − 10.4 | − 12.6 | − 11.5 | 0.6 |
| | Male | 21 | − 8.2 | − 13.1 | − 11.5 | 1.1 |
| | ?Adults | 4 | − 10.3 | − 12.3 | − 11.5 | 0.9 |

## Sex and age differences in adult population

When considering sexed adults, no significant differences in the $\delta^{13}C_{coll}$ or $\delta^{15}N$ of male ($n = 20$) and female ($n = 15$) bone collagen exist ($\delta^{13}C_{coll}$ $U = 129.00$, $p = 0.484$; $\delta^{15}N$ $U = 109.50$, $p = 0.180$). The adult sample was divided into three different age categories: young adults (16–35 years, $n = 13$), middle-aged adults (35–50 years, $n = 14$) and old adults (> 50 years, $n = 8$). No differences were found in $\delta^{13}C_{coll}$ or $\delta^{15}N$ values among age groups (K–W test, $\chi^2$ (2) = 3.41, $p = 0.18$ for $\delta^{13}C_{coll}$; $\chi^2$ (2) = 0.08, $p = 0.96$ for $\delta^{15}N$).

## Carbon isotopic signatures from dental enamel in human samples

The descriptive statistics for the enamel samples can be found in Table 5 and are presented in Fig. 3a. The average $\delta^{13}C_{ap}$ for all teeth is − 11.2 ± 1.3‰ (min − 3.1‰, max − 6.4‰). There is greater intrapopulation variation in $\delta^{13}C_{ap}$ than $\delta^{13}C_{coll}$ (ranges = 6.7 and 1.9‰, respectively). Cases 11931, 12063 and 7968 are conspicuous with $\delta^{13}C_{ap}$ values of − 6.5‰ (M2), − 6.4‰ (M3) and − 8.2‰ (M1), respectively. They can be considered as outliers since their values differ from the average more than two standard deviations.

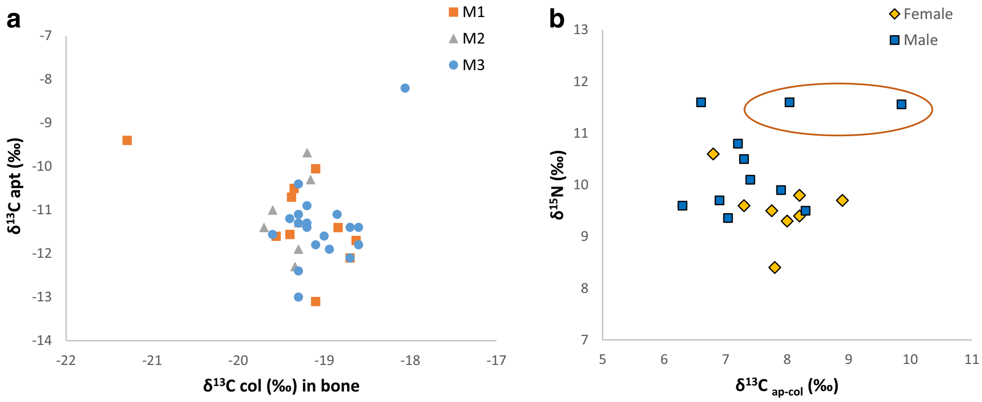
## Age differences

Figure 3a shows little difference in $\delta^{13}C_{ap}$ values between permanent tooth type (M1, M2 and M3), with no single tooth type demonstrating a clear enrichment or depletion in $\delta^{13}C_{ap}$ values. This was confirmed using a Kruskal–Wallis $H$ test ($\delta^{13}C_{ap} = \chi^2$ (2) = 0.290, $p = 0.870$). As the enamel of these teeth forms at different, although slightly overlapping ages, a lack of consistent pattern may suggest no systematic differences in diet at different stages of childhood (infancy to approximately 12 years).

## Sex differences

Like the collagen values, no significant differences in the stable carbon isotope apatite values existed between men and women for either tooth type (M3 ($U = 29.5$, $p = 0.15$, $n = 20$), M2 ($U = 2.5$, $p = 0.14$, $n = 8$)). Tooth crowns develop during infancy and childhood and undergo no structural change once complete, while bone constantly remodels

**Fig. 3** **a** Data comparing $\delta^{13}C_{coll}$ from bone collagen (ribs) and $\delta^{13}C_{ap}$ from teeth, with M1, M2 and M3 plotted in different series, one sample per individual with the exception of ID3801 (M2 and M3) and ID3863 (M2 and M3). **b** Graph comparing $\Delta\delta^{13}C_{ap\text{-}coll}$ with $\delta^{15}N$; females and males are in different series; regression was computed with both sexes and excluding the two outliers inside the ellipse



throughout life. Adult diet obtained by bone collagen can be compared with data from apatite measured in M3, since this tooth can represent childhood diet (8–12 years) (Ubelaker 1999). In general, males and females present similar spacing between collagen and apatite values, $\Delta\ \delta^{13}C_{ap\text{-}col}$ ♀ = 7.9 ± 0.6‰ and $\Delta\delta^{13}C_{ap\text{-}col}$ ♂ = 7.5 ± 1.0‰. Although M3 can show a great variability in its age of development, the obtained results again suggest no differences between sexes but importantly extend this notion to childhood (Fig. 3a). However, when $\Delta\delta^{13}C_{ap\text{-}col}$ is plotted with $\delta^{15}N$, there is an observable trend (see Fig. 3b) in that males tend to have higher $\Delta\delta^{13}C_{ap\text{-}col}$ and $\delta^{15}N$ values (− 7.5 ± 01.0 and 10.4 ± 0.9‰, respectively) while females seem to have lower $\Delta\delta^{13}C_{ap\text{-}col}$ and $\delta^{15}N$ (−7.9 ± 0.6 and 9.5 ± 0.6‰, respectively). When considering the results of the comparison, we have to remember that the data from apatite reflects only subadult consumption and the values from collagen indicate diet from last years of life.

## Discussion

### Staple food resources consumed by the inhabitants of Écija

This paper aims to reconstruct the staple foods and available resources for the inhabitants of Écija with a view to understanding wider issues influencing the population and contextualise this with other regions of Iberia. Due to the relationship between human isotope values and consumed animal values, it is important to discuss the faunal results prior to considering human values. The comparison of $\delta^{13}C$ and $\delta^{15}N$ values between the large herbivores and the rabbit, an animal most likely eating $C_3$ plants, shows that both caprine (goat/sheep) and cattle are likely to be foddered on or freely ate $C_3$ plants, but there may have been a very minor use of $C_4$ resources.

Although medium–large herbivores do not differ significantly in average isotopic signals, and overlap is present, the intragroup variation in values may signal different strategies of management for cattle and sheep/goat. Écijan cattle tend to have more elevated $\delta^{13}C$ and slightly lower $\delta^{15}N$ values than caprine. Similar $\delta^{13}C$ differences were observed by Alexander et al. (2015) for later Islamic fauna in the central-east of Iberia, while the opposite was observed in a pre-Islamic Christian population from the North-West region (López-Costas and Müldner 2016). Furthermore, although our sample size is small, cattle have greater isotope value variation than caprine, again also observable in other studies (see Guede et al. 2017; Alexander et al. 2015). Transhumance has been important strategy in Iberia from the Roman period onwards (Glick 1995). Herds of sheep and goat, valued more for meat, were moved to better grazing pastures at certain times of the year. Such movement may be notable from Écijan caprine data in Zakrzewski's (2010) mobility study; caprines have more elevated Sr values than humans, perhaps reflecting inhabitation in an area away from the town, such as nearby hill or mountain regions. Research by García-García (2017), who draws on Davis (2008) and Davis et al. (2013), has highlighted the possibility that a system for the provision of animal products from a specialised herding system existed in the region, which could explain the lower variation in caprine data. It is possible that we are seeing further evidence of this in our data. As cattle appear to have been less preferred for meat in comparison to caprine (Salas-Salvado et al. 2006), which could be viewed in the isotope data where humans appeared roughly one trophic level above caprines, and were valued for secondary products in the Islamic period, it is possible that they were kept closer to home and in smaller numbers. Thus, if individual or small groups of cattle were owned by different people/families, as opposed to in herds, there may be greater potential for foddering or pasturing differences, which could be the source of variation in the cattle data. However, we are conscious that our sample size is limited; so, here, we call for more dedicated isotopic research, such as that carried by Sirignano et al. (2014) on animals from northern Iberia, as it would be enlightening about lifeways in Iberia more generally, and how husbandry practices changed.

Carbon data suggests that Écijans had a diet mainly based on $C_3$ plants, and this appeared stable across the use of the cemetery, suggesting no shift to $C_4$ plants. This supports historical research that highlights Écija as an important wheat and barley-producing region (García-Baena 2006). The limited indication of $C_4$ plants may reflect the intake of some animals foddered on millet or sorghum, which could also be grown in the area (although see next paragraph). However, the contribution of $C_4$ plants to human or animal diet appears scant. The data do not suggest significant consumption of fish and marine resources, a result consistent with the location of Écija and historic information on food traditions in this inland area of Andalucía, where the base of diet was likely to be cereal, with limited meat consumption by the majority of the population. Only one male (7968) had $\delta^{13}C_{ap}$ values suggestive of a greater consumption of $C_4$ resources, although he also had one of the highest $\delta^{15}N$ values. This individual may differ in diet to the rest of the population and/or come from another location. Given that this man was in the earliest layers of the cemetery, analysis of oxygen and strontium values might be insightful for ascertaining if he migrated. Another point to consider is the possible effect of shifts in water management mentioned in historical sources (Martín Civantos 2016); however, the $\delta\ ^{13}C$ in crops due to irrigation seems to be very site-specific (Flohr et al. 2011) and results risky to interpret its influence in animal and human signals.

Dietary reconstruction based on bioapatite ($\delta^{13}C_{ap}$) together with the combination of $\delta^{13}C_{ap}$ vs. $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap\text{-}coll}$ vs. $\delta^{15}N$ may suggest the consumption of a $C_4$ plant with high $^{13}C$ values but with very low protein. Sugarcane is consumed through the production of molasses which is composed of carbohydrates rather than plant fibres; therefore, its high $\delta^{13}C$ does not affect human collagen isotopic signal which is related to protein diet. Similar results have been linked with sugarcane consumption, for example in the Pacific Marianas (Ambrose et al. 1997). Sugarcane was probably introduced into Iberia during the Islamic period (Watson 1974); however, it has been rarely introduced into the discussion of palaeodietary reconstruction using isotopes, because its low protein content makes it only detectable in carbon apatite values and no research has included $\delta^{13}C_{ap}$ in their isotopic analyses until now. Importantly, the Guadalquivir valley, in which Écija is situated, is recorded as a successful sugarcane-producing region (Sato 2015). The consumption of sugarcane, which would have not been dietary staple, may explain the slight shift in carbon values towards those expected for communities consuming $C_4$ plants, and could be geographically and historically expected for Écija. However, as not all individuals show evidence for its consumption, it is possible that it is not yet a universal commodity, which fits with ideas that it was initially for family consumption in the first few centuries of Islamic rule (Perez Vidal 1973). In addition, we are not able to ascertain whether its consumption was limited to children as we were only able to test enamel.

Recalling the difference in $\delta^{15}N$ values between humans and herbivores, it appears that animal protein was being consumed. However, some human $\delta^{13}C$ and $\delta^{15}N$ values differ little to averages for cattle and caprine. Initially, this suggests that some individuals may have been almost vegetarian, signalling intragroup diversity in diet. As meat and dairy products may have been more expensive food items, it could reflect the mixed economic status of individuals buried at the cemetery. However, as highlighted previously, there is a great degree of variability in the animal values, especially the $\delta^{15}N$ values for cattle. It is quite possible that individuals close to the cattle and caprine averages were eating protein, but from animals at the lower end of $\delta^{15}N$ range demonstrated.

## Implications for socio-politico and physical environment

One feature often assessed in Medieval populations is sex differences in data and how this links to gender ideals. In particular, there is significant interest in whether sex divisions appear in the Islamic period due to the arrival of new Islamic gender ideology (Inskip 2013). Sex differences are present in other biological data, including activity-related skeletal modifications at Écija (Inskip 2013, 2016), while more generally historic sources highlight that there was a gender division of labour and activity (Shatzmiller 1994) and space (Díaz-Jorge 2012) in Medieval Iberia. The collagen data suggests no significant differences between males and females in terms of diet, and apatite values potentially show that this can be largely extended to boys and girls. However, the combination of collagen and apatite values might hint at greater consumption of sugarcane by females (girls). This suggests that although base diet did not differ between the sexes, there may have been subtle variances between males and females.

There is no historical evidence to suggest that there should be differences in the diets of adults and children post-breast feeding. The decrease in $\delta^{15}N$ values in individuals aged 1.5 to 3.0 years of age is consistent with weaning beginning in the first or second year of life. With no significant variation in carbon collagen values and a lack of consistent difference in apatite values between teeth, it suggests that childhood diet did generally not vary from adults after being weaned.

The isotope data are potentially revealing about the environment Écijans inhabited. Arid temperatures and high salinity have been identified as the cause of abnormally high values for $\delta^{15}N$ (Ambrose 1991; Heaton 1987; Britton et al. 2008; López-Costas and Müldner 2016). Today, Écija is renowned for its high temperatures and salinity (Fernández et al. 2002), as well as nearby "Altiplano de Écija". However, with the exception of a few high cattle values, which may relate to husbandry practices, Écija's human $\delta^{15}N$ values are moderate, if not low for the time period (see Table 6), as might be expected if environmental conditions and salinity were a

**Table 6** Stable isotope values from other studies of Medieval material from Iberia

| Site | Date | Religion | *n* | $\delta^{13}$C (‰) | SD | Range | Cattle human $\delta^{13}$C$_{coll}$ (‰) offset | Sheep human $\delta^{13}$C$_{coll}$ (‰) offset | $\delta^{15}$N (‰) | SD | Range | Cattle human $\delta^{15}$N (‰) offset | Sheep human $\delta^{15}$N (‰) offset |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ibiza[3] | 4th–6th | C | 60 | − 19 | 0.4 | − 19.9 to − 18.0 | 2 | 1.8 | 11.1 | 1.1 | 8.3 to 13.6 | 3.4 | 5.4 |
| A Lanzada[7] | 5th–7th | C | 15 | − 14.3 | 0.7 | − 16.5 to − 12.8 | 6.1 | 5.6 | 12.8 | 0.5 | 12.0 to 12.8 | 5.7 | 5.3 |
| Aistra[6] | 8th–9th | C | 35 | − 19 | 1 | − 22.0 to − 16.7 | 1.7 | – | 7.9 | 1 | 6.8 to 12.1 | 3.1 | – |
| San Salvador de Valdedois[4] | 10th–13th | C | 12 | − 19 | 0.4 | − 19.6 to − 18.0 | 2.6 | 0.2 | 9.7 | 0.9 | 8.8 to 12.2 | 4.6 | 2.7 |
| San Pedro de Nora[4] | 12th–15th | C | 12 | − 18.3 | 1.8 | − 19.8 to − 13.1 | 3.3 | 0.9 | 10.3 | 1 | 8.8 to 11.3 | 5.2 | 3.3 |
| San Miguel de Lillo[4] | 12th | C | 16 | − 17.5 | 2.5 | − 19.5 to − 10.7 | 3.2 | 0.8 | 10.4 | 1 | 9.2–13.9 | 5.3 | 3.4 |
| Jaca[1] | 13th–15th | C | 27 | − 18.3 | 1.2 | − 17.0 to − 15.3 | – | – | 10 | 0.9 | 8.6 to 10.6 | – | – |
| Colegiata, Gandia[2] | 13th–16th | C | 20 | − 17.2 | 1 | − 18.7 to − 15.0 | 0.6 | 2.1 | 10.3 | 0.8 | 8.8 to 12.0 | 3.3 | 6.3 |
| Tauste[5] | 8th–10th | I | 11 | − 19.1 | 0.4 | − 19.5 to − 18.4 | 2.5 | 0.1 | 15.3 | 1.8 | 10.8 to 17.0 | 10.2 | 8.3 |
| **Écija** | **9th–12th** | **I** | **55** | **− 19** | **1** | **− 19.7 to − 18.1** | **0.2** | **1.3** | **9.8** | **1.3** | **8.0 to 11.6** | **2.9** | **2.2** |
| Ibiza[3] | 10th–13th | I | 24 | − 18.1 | 1.3 | − 19.4 to − 13.1 | 1.3 | 0.8 | 10.9 | 1 | 8.5 to 12.5 | 3 | 4.6 |
| Zaragoza[1] | 10th–12th | I | 37 | − 19 | – | – | – | – | 10.9 |  |  | – | – |
| Benipeixcar[2] | 15th–16th | I | 20 | − 16.4 | 1 | − 18.0 to − 14.2 | 1.4 | 2.9 | 10.7 | 0.6 | 9.2 to 11.9 | 3.7 | 6.7 |

C, Christian; I, Islamic. Current study highlighted in bold

1, Mundee (2009); 2, Alexander et al. (2015); 3, Fuller et al. (2010); 4, MacKinnon (2015); 5, Guede et al. (2017); 6, Quirós Castillo (2013); 7, López-Costas and Müldner (2016) significant factor in dictating $\delta^{15}N$. For example, at Tauste, a contemporary Islamic cemetery in northern Iberia with high soil salinity, the average $\delta^{15}N$ human value was 15.3‰ with a max of 17‰ (Guede et al. 2017). Fernandez et al. (2002) have argued that modern human activity has been a significant contributor to the high salinity in the town today, and it is interesting that our results support this situation. This infers that either the conditions were different or that medieval individuals were using a different water source. Regardless, it is very interesting that the values differ so significantly to Tauste even though there are similar environmental conditions. Further research on inhabitants from other parts of Écija may be enlightening in this regard.

## Écija in context

When we place Écija in context with results from other Iberian isotopic studies, it is important to take into account not only the faunal values as well as the human data but also the offset between humans and animals. Observing Table 6, a complex picture emerges which does not map neatly on to any one specific factor (religion, time, environment and social factors). First, it is necessary to highlight two sites with outstanding results. As already mentioned, Early Islamic Tauste appears to be unique in its nitrogen values, a feature attributed to extreme salinity in the area (Guede et al. 2017). Second, Lanzada, a pre-Islamic site in the north with very high carbon and nitrogen values, is argued to represent a mixed marine and millet-based diet. These cases in particular show that local circumstances are very important in dictating the values observed and that trying to ascertain general trends is difficult in a region like Iberia where there is both a complex geology and varying social and political structures. Already, this highlights the importance of doing regional studies, which is important in revealing these complexities.

One of the big questions surrounding life in medieval Iberia is whether there are detectable differences between Christian and Islamic communities. In order to assess this, it is necessary to consider each religious group separately. Table 6, which outlines data for other isotopic studies, shows similarity in $\delta^{13}C$ values between Écija and contemporary northern and central Islamic sites at Zaragoza and Tauste (Alexander et al. 2015; Guede et al. 2017; Mundee 2009). The two other Islamic sites, Benipeixcar and Ibiza, differ with both presenting values consistent with greater $C_4$ consumption. However, it is notable that Écija is lower in offset with cattle than both these sites, yet the offset with caprine at Écija is somewhat higher than that in Tauste or Ibiza. In terms of $\delta^{15}N$ values, Écija is similar to other Islamic sites, with the exception of Tauste (discussed in previous texts), but when assessing the offset with cattle and caprine, Écijans differ very little to caprine which is different to the other two sites. This infers that while there are similarities between these Islamic sites, there are still subtle differences between them that may relate to animal practices, human dietary patterns, but also potentially environmental variation. Of course, these issues may also be interrelated. In addition, while there are no sex differences in the data from Écija, sex differences are visible at Tauste (Guede et al. 2017). To explore this further, it would be valuable to assess other Islamic sites in the south of Iberia and to have faunal data for Zaragoza. Turning to the Christian groups, we can see that, in general, there is more variation in the human values but also the human and animal offset values. Importantly, this variation is observed in the pre-Islamic and Islamic period Christian sites. Some of this variation is likely to relate to the fact that some of the sites are small and rural in nature, which would likely differ in dietary patterns to larger settlements, but potentially also between rural communities. It would be useful to have similar rural data for Islamic sites to understand if similar trends exist.

Given the variation that exists within Islamic and Christian sites, it is very difficult to ascertain whether there is a pattern typical of either religious identity or how things changed over time. For example, Écija's isotope values most closely resemble those of the rural 10th to 13th century Christian individuals at San Salvador de Valdedois, in the north (Table 6). However, this does not mean that religious differences did not exist, but as isotopes only provide an overview of diet, and many diets can appear isotopically similar, other evidence, including botanical, palaeopathological and zooarchaeological, is required to tease out these differences. The possible identification of sugarcane consumption at Écija may be significant here. As there was already a strong relationship between Islamic practices and sugar consumption by the 9th century (Sato 2015), to ascertain if it could be a useful indicator of Islamic identity, it is necessary to assess if other Islamic and Christian groups show similar signals and how this might relate to time.

Although the data are limited, when we place the carbon values from Écija in context with other sites, it appears that time has more of an influence than region or religion. Écija is similar to its contemporary Islamic and Christian sites in having carbon values which do not indicate significant $C_4$ plant consumption. Archaeobotanical research based on 10th to 12th century Northern Iberian cities has also found millet to be present in very low quantities. Excluding A Lazada, a pre-Islamic Christian community with a clear $C_4$ signature (López-Costas 2012), we only see strong evidence for millet or sorghum consumption from the 12th century onwards. The two Islamic sites with evidence of significant $C_4$ consumption are the late medieval community at Benipeixcar, perhaps representing a group whose diet had shifted due to changes in status (see Alexander et al. 2015), and at Ibiza, where its island status means that migration patterns, trade and/or local circumstances may have resulted in differing isotopic values to mainland sites (see Fuller et al. 2010; Nehlich et al. 2012). For example, food could have been bought to the island. This potentially suggests that although the southern Iberian environment might have been suitable to $C_4$ plant production and technology may have improved to allow its production, $C_4$ plants became a staple only until well after the 11th century. Overall, this shows that the exploitation of $C_4$ plants is likely to be related not only to the possibilities of cultivation but also to the multitude of social factors, including status, group preference, as well as practicalities (i.e. relation with other crops).

Although the faunal sample sizes are small for the sites tested, and therefore difficult to compare statistically, Écija is interesting due to the low offset between its animals and humans. Écijans have the lowest nitrogen offset of any of the groups where faunal data is available, regardless of region, religion or time (see Table 6). It is unclear how typical this offset is for an Islamic town as only Islamic Tauste and Ibiza have available faunal data and both are unique in their circumstances. In comparison to the Christian sites, this may reflect a lack of other resources that could increase carbon values in humans, such as fish, which given that nearly all the Christian sites are not too distant from the coast would make sense. It may also reflect the consumption of fish as part of a Christian diet. More studies on sites such as Écija are needed to assess this further.

## Conclusion

Stable nitrogen and carbon isotope values, measured from collagen and apatite, were assessed in the southern Iberian population of Écija in order to fill a gap in our knowledge on dietary resources in Iberia during the medieval period. This aimed to improve our understanding of important factors influencing the lives of people during a unique period of time punctuated by important socio-cultural changes. Overall, Écija's isotopic data demonstrate that individuals in the town had a $C_3$-based economy, consumed some animal protein, but lacked strong evidence for significant $C_4$ plant consumption, such as millet and sorghum and marine resources, although, juxtaposition of $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$ hints that sugarcane may have become part of Écijans' diet, though not by everyone. Interestingly, the nitrogen values are moderate compared to what could be expected given the environmental conditions, and despite Écija's suitability for millet and sorghum production, it is not observable in the data. The rich agricultural land surrounding Écija, coupled with cultural preference, may have limited the desire for millet or other $C_4$ plant production.

Comparison of Écija's faunal and human data with other medieval Christian and Islamic sites shows that while there is some similarity between Islamic sites in the north and central parts of Iberia, the variation between them is marked and overlaps with Christian sites. As such, at present, we cannot typically identify an Islamic or Christian diet, or between northern or southern sites more generally. Based on the current data, more important factors may include time, changing social–political situations, local environment and/or available resources. Unsurprisingly, a complex picture emerges which highlights the importance of undertaking regional studies. Only when we have a good understanding of the variation in dietary practices and resources across the region can we start to assess the significance of sociocultural and environmental change. To move forward, more dedicated studies of faunal material accompanied by a greater diversity of sites across the region are necessary.

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