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Feeding management strategies among the early Neolithic pigs in the NE of the Iberian Peninsula

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Abstract

The socio-economic relevance of domesticated animals during the Early Neolithic in the Iberian Peninsula is indisputable, yet we essentially know little about the way they were managed. Among domesticated animals, pig (*Sus domesticus*) was a common food source and previous studies have shown the potential of stable isotopes for assessing variability in pig diet in relation to husbandry practices. Nevertheless, this approach has never been applied to the earliest pigs in the Iberian Peninsula. We analyzed the carbon and nitrogen stable isotope composition of pig bone collagen from several Early Neolithic sites in the NE Iberian Peninsula. While pig $\delta^{13}C$ values were similar across different populations, there were significant differences in $\delta^{15}N$ values between sites. These are attributed to different pig husbandry systems, which may reflect distinct social and spatial organization and interaction

with environmental conditions during the Early Neolithic in this region.

Introduction

The establishment of farmers and their domesticates marked a turning point in the socio-economic and cultural landscape of the western Mediterranean in the Middle Holocene. Livestock management practices in the Early Neolithic contributed to the emergence of new work processes, integrated new products in the human diet, and catalyzed the transformation of natural environments (Barker, 2005; Blondel, 2006; Zeder, 2008). With some exceptions in the north of the Iberian Peninsula, the hunting of wild game declined in most regions, while livestock became the most important source of animal meat and other secondary products (Saña, 1998; Guerra et al., 2008; Marín & Morales, 2009; Altuna & Mariezkurrena, 2011). The farming practices included complementary exploitation of pig, cattle, sheep and goat (Altuna & Mariezkurrena, 2011; Saña, 2013).

Among domesticated animals, pigs (*Sus domesticus*) played a role as meat supplier during the establishment of farmers in the Iberian Peninsula (Saña, 1998, 2013). Their relative abundance varied considerably between sites dated to early Neolithic periods (from 4 % to 23.9 % of domestic animals) suggesting different scales of husbandry regimes (Saña, 2013; Saña et al., 2015), but the form of these practices still remains highly elusive. Traditional husbandry practices may have involved home-based systems with complete to partial stabling of herds in close proximity to settlements, or extensive management of herds in semi-free to free-range regimes. While these management practices are known from modern traditional communities in northern Mediterranean areas (Albarella et al., 2007; Hadjikoumis, 2012), and have been also postulated for prehistoric groups in Europe (Balasse et al., 2016), their occurrence during the Neolithic in the NE Iberian Peninsula remains unclear. This gap in our knowledge prevents a full understanding of the socio-environmental significance of animal management practices during the establishment of early farming communities in this region.

Husbandry practices usually imply some degree of human control over animal diet in order to ensure their adaptation to and performance in local environmental conditions, promote health and prevent diseases. Due to their omnivorous nature, pigs have access to a broad range of food sources which can be mediated by cultural practices. Under human control, pig diets can be manipulated and supplemented with agricultural and animal products. Individual animal diets can be investigated using stable carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) isotope compositions of organic tissues, such as collagen in bone (DeNiro & Epstein, 1978; Schwarcz & Schoeninger, 1991; Ambrose, 1993; Sealy, 2001). Previous studies have demonstrated the potential of bulk collagen carbon and nitrogen stable isotopes for determining the degree of omnivory in pig feeding behaviour, and this information has been used to reconstruct pig management strategies in prehistoric and historic times (Matsui et al., 2005; Pechekina et al., 2005; Hamilton et al. 2009; Hamilton & Thomas, 2012; Madgwick et al., 2012; Balasse et al., 2015, 2016).

In this paper we investigate the stable isotope ecology of pigs from six Early Neolithic sites in the NE Iberian Peninsula dating between ca. 5700 and 4200 cal BC (Fig. 1). Using stable carbon and nitrogen isotope analysis we assess the main dietary components of the pigs in relation to wild and domestic herbivores, omnivores and carnivores, and discuss the implications for understanding the variability of husbandry practices in this region.

Stable isotope analysis of bulk collagen

Collagen is the major protein in bone and its carbon and nitrogen isotope composition are indicative of individual diet over a relatively long period of time (e.g. 5-15 years depending on the age; Hedges et al., 2007; Hedges & Reynard, 2007). Dietary information derived from collagen $\delta^{13}C$ and $\delta^{15}N$ values is generally biased toward the protein fraction in the diet (Schwarcz & Schoeninger, 1991; Ambrose & Norr, 1993; Sealy, 2001). In diets with inadequate amounts of proteins for tissues synthesis the carbon isotopes may also originate from other macronutrients such as lipids and carbohydrates (Tieszen et al., 1983; Ambrose & Norr, 1993; Jim et al., 2004; Craig et al., 2013). Stable carbon isotopes differ greatly between terrestrial, marine and estuary ecosystems (Schoeninger & DeNiro, 1984; Bocherens et al., 1991, 1995), and between plants with different photosynthetic pathways (C_3 and C_4 plants) (O'Leary, 1988), thus providing a means of discriminating between macronutrients from distinct isotopic sources in diet.

Nitrogen isotopes are obtained exclusively from dietary protein, with $\delta^{15}N$ values generally reflecting the trophic position of the food source due to relatively large and predictable isotopic fractionations (ca. +3‰ to +6‰) through the foodweb (Schoeninger & DeNiro, 1984; Ambrose, 1993; O'Connell et al., 2012). Moreover, bulk collagen $\delta^{15}N$ values of humans and animals from agricultural contexts can potentially record changes in the abundance of ^{15}N in plant-soil systems due to land management practices, such as the addition of animal fertilizers (Bogaard et al., 2007; Szpak, 2014). When placed within the context of the local ecosystem, nitrogen stable isotopes can thus provide valuable information about the trophic level of food sources in pig diet, as well as spatio-temporal changes in agricultural strategies (Müldner & Richards, 2005; Hamilton & Thomas, 2012; Madgwick et al., 2012; Balasse et al., 2015, 2016).

Archaeological settings

Faunal remains were sampled from six early dated Neolithic sites located in the NE Iberian Peninsula (Table 1), distributed from the Eastern Pyrenees to the Mediterranean coast. Their elevations range from 960 m asl (cova del Frare) to 7 m asl (Caserna de Sant Pau). The majority of the sites are open settlements in coastal (Reina Amàlia, Caserna de Sant Pau and Serra de Mas Bonet) and inland areas (La Draga), while others are inland cave sites (cova del

Frare and Can Sadurní). Faunal and plant remains have been widely recovered in all sites during excavations, with zooarchaeological and archaeobotanical studies being developed over the past several years.

La Draga is a lakeshore settlement ^{14}C dated to 5201-4721 cal BC at Lake Banyoles, 170 m asl (Palomo et al., 2014; Terradas et al., 2015). The site is estimated to encompass approximately 8000 m^2, while an area of about 800 m^2 has been excavated. A large fraction of the archaeological record is underwater or in waterlogged environments, which has allowed excellent preservation of organic remains. The subsistence economy involved the exploitation of domestic and wild animals including mammals, fish, birds and molluscs (Saña, 2011, 2013). Agricultural practices are attested to by rich macrobotanical assemblages including *Hordeum distichum, Triticum durum/turgidum, Triticum aestivum, Triticum dicoccum, Triticum monococcum, Tricticum* sp*., Vicia faba* and *Pisum sativum* (Buxó, 2007; Antolin & Buxó, 2012; Antolín et al., 2014). Farming was the main economic activity, followed by hunting and gathering of wild plants (Saña, 2013; Antolín et al., 2014).

Reina Amàlia and the adjacent site of Caserna de Sant Pau are coastal settlements located in Barcelona. At 25 m asl and ^{14}C dated to 4611-4373 cal BC (González et al., 2011), the site at Reina Amàlia has a surface area of at least 200m^2, consisting of a group of habitation structures (50m^2), including burials, where the subsistence economy involved the exploitation of domesticated animals (*Sus domesticus, Ovis aries, Capra hircus* and *Bos taurus*), complemented with wild fauna (Saña & Navarrete, 2016). Agricultural practices are similarly attested to by the remains of *Hordeum vulgare* var. *nudum* and *Triticum aestivum/durum/turgidum* and *Triticum dicoccum* (Antolín, 2016). The site of Caserna de Sant Pau has been successively occupied during the Neolithic, with the phase analyzed in this study ^{14}C dated to 5372-5076 cal BC (Molist et al., 2008). The excavated area corresponds to approximately 800m^2. This site also consists of structures (silos), and individual and double burials. Subsistence included the exploitation of domestic animals (*Sus domesticus*, *Ovis aries*, *Capra hircus* and *Bos taurus*) (Colominas et al., 2008) and plants (*Hordeum vulgare*, *Hordeum vulgare* var. *nudum*, *Triticum aestivum*/*durum*, *Triticum dicoccum*, *Vicia faba* and *Pisum sativum*) (Buxó & Canal, 2008), along with wild resources (Buxó & Canal, 2008; Colominas et al., 2008; Molist et al., 2008).

Cova del Frare is a cave located in the massif of Sant Llorenç de Munt at 960 m asl, and was occupied from the Early Neolithic to the Bronze Age. The Early Neolithic deposits analysed in this work were ^{14}C dated to 5216-4993 cal BC (Martín et al., 2009). The cave has been interpreted as a seasonal dwelling for Neolithic shepherds, with storage bins, household waste and tool production debris having been recovered at the site (Martín et al., 2010). The local economy included four main domestic animals - *Sus domesticus*, *Ovis aries*, *Capra hircus* and *Bos taurus*. No archaeobotanical analyses have been performed on the site as it was excavated in the early 1980s when sampling for such analyses was not common practice in the study area.

Can Sadurní is a cave located in the massif of the Serra de Garraf at 420 m asl. In this work, we analyzed Early Neolithic deposits from the site ^{14}C dated to 5291-4710 cal BC (Layer 17) and 4456-4335 cal BC (Layer 10b / 11) (Edo et al., 2011). Plant remains suggest that the cave was used as a stall during the Early Neolithic (Edo et al., 2011), and this seems to be supported by archaeozoological analysis (Saña et al., 2015). The subsistence economy involved the exploitation of domesticated animals (*Sus domesticus, Ovis aries, Capra hircus* and *Bos taurus*) (Saña et al., 2015), and agricultural practices are well represented by several crops, such as *Hordeum vulgare, Hordeum distichon, Hordeum vulgare* var. nudum, *Triticum aestivum/durum, Triticum dicoccum, Triticum monococcum, Lens culinaris, Pisum sativum, Papaver somniferum* and possibly also *Linum usitatissimum* (Antolín, 2016; Antolín et al., 2017). Wild resources were also exploited at the site (as evidenced by *Arbutus unedo, Pistacia lentiscus, Pinus* sp., *Quercus* sp. and *Vitis vinifera* subsp. *sylvestris,* and *Sus scrofa, Capra pyrenaica* and *Capreolus capreolus*) (Blasco et al., 1999; Antolín et al., 2015; Saña et al., 2015).

Finally, Serra de Mas Bonet is a settlement in Vilafant, at 75 m asl and ^{14}C dated to 4900-4600 cal BC (Rosillo et al., 2010). The analysed material derived from two structures interpreted as silos, however their spatial distribution appears random and the total surface area of the site could not be assessed. Farming was the principal economic activity at the site, with the rearing of domesticated animals (*Sus domesticus, Ovis aries, Capra hircus* and *Bos taurus*) (Saña, unpublished). No direct evidence of plant remains was found for this settlement phase, probably due to poor sampling or preservation conditions of the organic remains at the site (Antolín, 2016).

Material and Methods

Selection of faunal samples

From the six Early Neolithic sites, 92 pig individuals were selected from layers dated between 5372-5076 to 4456-4335 cal BC, for stable carbon and nitrogen isotope analysis (Tables 1, 2). In order to establish the local $\delta^{13}C$ and $\delta^{15}N$ isotopic baselines of the pigs, we also selected a range of herbivores (n = 70), including domestic (*Ovis aries, Capra hircus, Bos taurus*) and wild animals (*Cervus elaphus, Capra pyrenaica, Capreolus capreolus, Oryctolagus cuniculus*), carnivores (n = 15) (*Meles meles, Martes martes, Felis sylvestris, Canis familiaris, Vulpes vulpes*) and a few wild boar (n = 5) (*Sus scrofa*). Wild boar, which represents only a minor fraction of suids found at these sites, were previously distinguished from domesticated pigs based on osteometric data (Hain, 1982; Albarella et al., 2005; Altuna & Mariezkurrena, 2011), using a data-driven approach of Payne & Bull (1988) and Albarella et al., (2009) (SI1-2). Samples for stable isotope analyses consisted of adult specimens, and included the diaphysis of long bones, maxilla and mandibular diastema. Whenever possible, specimens were selected to represent individual animals by sampling the same-sided portion of a specific element. Specimens available from Reina Amàlia and Caserna de Sant Pau were combined to form a single assemblage (Reina Amàlia-Caserna de Sant Pau) as they were located adjacent to one another.

Collagen extraction and stable isotope analysis

Collagen extraction and stable isotope analysis were performed at the Unitat d'Antropologia Biològica (Departament Animal Biology, Plant Biology and Ecology) and Laboratori d'Arqueozoologia (Department of Prehistory) at the Autonomous University of Barcelona (Spain). Some samples were also extracted and analysed at the BioArCh facilities in the Department of Archaeology, University of York (UK). Collagen extraction followed similar protocols in both labs. Bones were cleaned mechanically to remove the surface and the extraction followed a modified Longin method (Brown et al., 1988); details can be found in previous studies (e.g. Craig et al., 2010). In short, shards of bones (ca. 200 to 300 mg) were demineralised using 0.6 M HCl, at 4°C for several days, then rinsed with ultrapure water (milli-Q®) and gelatinised with 0.001 M HCl at 80°C for 48 h. Samples were then ultrafiltered (30 kDa, Amicon® Ultra-4 centrifugal filter units; Millipore, MA, USA), frozen and freeze dried.

Collagen samples (0.3 mg) were analysed in duplicate using a Thermo Flash 1112 elemental analyser (EA) coupled to a Thermo Delta V Advantage isotope ratio mass spectrometer (IRMS) with a Conflo III interface, at the Institute of Environmental Science and Technology, Autonomous University of Barcelona. The international laboratory standard IAEA 600 (caffeine) was used as a control. The average analytical error was <0.2‰ (1σ) as determined from the duplicate analyses of $\delta^{13}C$ and $\delta^{15}N$. Some samples were analyzed at the University of York (1 mg) in duplicate or triplicate on another EA-IRMS in a GSL analyser coupled to a 20-22 mass spectrometer (Sercon, Crewe, UK). The analytical error for both $\delta^{13}C$ and $\delta^{15}N$ values, calculated from repeated measurements of each sample and measurements of the bovine control from multiple extracts, was also <0.2‰ (1σ). The standard used for $\delta^{13}C$ was Vienna PeeDee Belemnite (V-PDB), and the standard for $\delta^{15}N$ was air N_2 (AIR). Samples (n = 3) and in-house collagen standards (n = 1 bovine control) were analyzed in both IRMS system to ensure accuracy.

Comparison between $\delta^{13}C$ values of wild and domestic herbivores, pig, wild boar, and carnivores was performed using one-way ANOVA ($\alpha = 0.05$), after checking for normal distribution with the Shapiro-Wilk test for normality ($\alpha = 0.05$). The null hypothesis that the data were normally distributed was rejected for the $\delta^{15}N$ values. Thus comparison between the $\delta^{15}N$ values was performed using the Kruskal-Wallis test ($\alpha = 0.05$). All statistical tests were performed in PAST 3.x (Hammer et al., 2001).

Results

Collagen preservation

The results of the stable isotopes and collagen quality indicators are reported in the figure 2 and table 2. Out of a total of 182 specimens, collagen was successfully extracted from 100 (55%). Collagen yields were extremely variable, ranging from 0.4 to 10.6 mg. The C% and N% ranged from 27% to 47%, and 10% to 17% respectively, with C:N ratios ranging from 3.1 to 3.6 and falling within the values proposed by DeNiro (1985) and Van Klinken (1999) for preserved collagen. We also applied a cut-off of 13% and 4.8% for C% and N%, respectively, as recommended by Ambrose (1990, 1993).

$\delta^{13}C$ values

The average $\delta^{13}C$ values of pigs exhibited little variability between sites (Fig. 2), ranging from -20.6 ± 0.6‰ (Reina Amàlia-Caserna de Sant Pau; n = 16) to -19.6 ± 0.7‰ (Can Sadurní; n = 3). However, pigs from Can Sadurní were significantly enriched in ^{13}C by approximately 1‰ compared to La Draga (n = 24) and Reina Amàlia-Caserna de Sant Pau ($p = 0.003$, $f = 4.37$). The average $\delta^{13}C$ values of herbivores ranged from -20.6 ± 0.7‰ (Reina Amàlia-Caserna de Sant Pau; n = 6) to -20.2 ± 0.7‰ (cova del Frare; n = 12), and were statistically indistinguishable between sites ($p = 0.6031$, $f = 0.516$). Moreover, no significant differences were found between the $\delta^{13}C$ values of wild and domestic herbivores at cova del Frare (n = 12) and La Draga (n = 10; $p > 0.05$), the only sites with sufficient specimens for statistical comparison. Comparison between pig and herbivore $\delta^{13}C$ values was possible for cova del Frare, Reina Amàlia-Caserna de Sant Pau and La Draga (Fig. 3A). At all of these sites, the $\delta^{13}C$ values of pigs and herbivores were statistically indistinguishable ($p > 0.05$). Due to the low number of sampled specimens (n = 5), the average $\delta^{13}C$ values of wild boar could not be compared between sites; however, the lowest wild boar $\delta^{13}C$ value was found at Reina Amàlia-Caserna de Sant Pau (-20.3‰), while the highest was found at La Draga (-19.3‰). Finally, the $\delta^{13}C$ values of carnivores varied between sites, but the highest variability was found at La Draga (n = 3), where the $\delta^{13}C$ values of European badger (*Meles meles*) ranged from -19‰ to -21.5‰.

$\delta^{15}N$ values

The average $\delta^{15}N$ values of pigs ranged from +5.1 ± 1.6‰ (La Draga) to +7.6 ± 1.1‰ (Reina Amàlia-Caserna de Sant Pau), and these differences were statistically significant ($p < 0.001$). In particular, pigs from Reina Amàlia-Caserna de Sant Pau and from Can Sadurní were enriched in ^{15}N by an average of 2.5‰ compared to specimens from La Draga and cova del Frare (n = 13) ($p = 0.030$). The average $\delta^{15}N$ values of herbivores ranged from +4.9 ± 1.1‰ (La Draga; n = 10) to +6.1 ± 1‰ (Reina Amàlia-Caserna de Sant Pau; n = 6). Although the herbivores from Reina Amàlia-Caserna de Sant Pau were on average enriched in ^{15}N by

~1.2‰ compared to those from La Draga and Can Sadurní, these differences were statistically insignificant ($p = 0.070$). The $\delta^{15}N$ values of wild and domestic herbivores were statistically indistinguishable at cova del Frare ($n = 12$) ($p = 0.852$). However, the domestic herbivores were significantly ^{15}N enriched by 0.6‰ compared to the wild ones at La Draga ($p = 0.028$). The $\delta^{15}N$ values of pigs were statistically indistinguishable from those of wild and domestic herbivores at cova del Frare and La Draga ($p > 0.05$). Conversely, the $\delta^{15}N$ values of pigs from Reina Amàlia-Caserna de Sant Pau were significantly higher by an average of 1.6‰ compared to the herbivores ($p = 0.008$) (Fig. 3B). The $\delta^{15}N$ values of wild boar were highly variable, with the highest values found at Can Sadurní (+7.6‰) and La Draga (+7.4‰), and the lowest at cova del Frare (+4.5‰) and Reina Amàlia-Caserna de Sant Pau (+5.6‰). Interestingly, the $\delta^{15}N$ values of wild boar from Reina Amàlia-Caserna de Sant Pau fall within the range of herbivores, and are lower than domestic pigs across most sites. The $\delta^{15}N$ values of carnivores were also variable across all sites, ranging from +6.5‰ (dog, *Canis familiaris*) to +12.6‰ (European badger) at La Draga. The $\delta^{15}N$ values of badgers justify their inclusion in the carnivore group.

Discussion

Source of carbon and nitrogen in pig diet

The $\delta^{13}C$ values of the analyzed specimens fall within the expected values for C_3 plant ecosystems (O'Leary, 1988), which dominated the vegetation composition in the NE Iberian Peninsula during the early-middle Holocene (Burjachs, 2000; Jalut et al., 2009; Revelles et al., 2016). Given the insignificant or small difference between the $\delta^{13}C$ (0.3‰) and $\delta^{15}N$ (0.6‰) values of domestic and wild herbivores for each site we combined them to obtain a more robust average isotopic baselines for interpreting pig $\delta^{13}C$ and $\delta^{15}N$ values. The $\delta^{13}C$ and $\delta^{15}N$ values of herbivores show very small to insignificant differences between sites, and present narrow ranges (3.3‰ and 3.7‰ respectively). Using a carbon isotope fractionation of ~5‰ between whole plant and consumer's bone collagen (Ambrose & Norr, 1993), and a correction (~+1.5‰) due to the fossil fuel effect when applied to pre-industrial ecosystems (Friedli et al., 1986; Hellevang & Aagaard, 2015), the highest $\delta^{13}C$ values in herbivorous animals (e.g. >-19‰) could be explained by the consumption of drought-resistant vegetation, such as shrubs (e.g. -23‰; Filella & Peñuelas, 2003). The $\delta^{13}C$ range of the pigs from all sites is even narrower compared to the herbivores (2.3‰) and their absolute $\delta^{13}C$ values generally overlap with the herbivore data (Fig. 3A). The results therefore indicate that pig diets were in general dominated by plant products.

Conversely to carbon, the average $\delta^{15}N$ values of pigs varied significantly among populations. The lowest $\delta^{15}N$ values were found in pigs from La Draga, followed by specimens from cova del Frare and Serra de Mas Bonet. In these sites the $\delta^{15}N$ values were generally comparable with their local wild and domestic herbivores (Fig. 2 and Fig. 3B), therefore likely reflecting a diet predominantly based on plant products. The highest $\delta^{15}N$ values were found in pigs from Can Sadurní and Reina Amàlia-Caserna de Sant Pau, where the $\delta^{15}N$ values were on average higher than the local herbivores by 2.5‰ and 1.4‰ respectively, and in some cases similar to carnivore $\delta^{15}N$ values (e.g. Can Sadurní).

Implications for pig husbandry practices

There is a general consensus that the variable contribution of animal and plant macronutrients to pig diet can potentially reflect the scale of husbandry practice in the past (Minagawa et al., 2005; Müldner & Richards, 2005; Pechenkina et al., 2005; Fuller et al., 2012; Hamilton & Thomas, 2012; Madgwick et al., 2012; Hammond & O'Connor, 2013; Halley & Rosvold, 2014; Balasse et al., 2015, 2016). This appears to be supported by ethnographic studies on traditional husbandry systems in Southern Europe (Italy, Spain, Greece and Corsica) that also reveal some variability in pig diet in relation to management strategies (Albarella et al., 2007, 2011; Isaakidou, 2011; Hadjikoumis, 2012). Given their omnivory and foraging habits, the nitrogen isotope composition of pig bone collagen can be derived from both animal and plant proteins. Pigs raised in a home-based system with complete or temporary stabling are expected to have a more controlled diet than free-range animals. Enclosed pigs may feed predominantly on plant materials (ground cereals and legumes), but due to a higher degree of human control they may have diets supplemented with domestic left-overs, including animal products. For pigs raised under this regime we could hypothetically expect collagen $\delta^{15}N$ values higher than local herbivores, although this would also depend upon other factors such as the proportions and quality of meat protein in their diets. By contrast, pigs reared in semi-free or free-range systems will likely obtain most of their nutrients from available plants, although this does not exclude some consumption of wild animals. Within this management strategy we might expect pig collagen $\delta^{15}N$ values to be compatible or very close to local herbivores. However, as discussed below, other interplaying factors may affect bulk collagen $\delta^{15}N$ values (Szpak, 2014).

The $\delta^{15}N$ values of pigs at Reina Amàlia-Caserna de Sant Pau and Can Sadurní suggest a relatively high proportion of animal sources contributed to their dietary proteins, which may be associated with a home-based management system, where pigs are enclosed or relatively free to forage within the settlement. This home-based system occurs in contexts where pigs are relatively abundant, such as at Reina Amàlia-Caserna de Sant Pau where they accounted for the 23.6% and 23.9% of domesticates, as well as in contexts where pigs were a minor component of livestock, such as at Can Sadurní, where pigs accounted for 7.5% of domesticates. In addition, the presence of neonate pigs found at Reina Amàlia-Caserna de Sant Pau (2.7% of pigs remains) supports the hypothesis that pigs were kept within the settlement. However, it has to be said that herbivores from Reina Amàlia-Caserna de Sant Pau, predominantly domestic animals, were on average enriched in ^{15}N by ~1.2‰ compared to those from La Draga and Can Sadurní. They suggest some degree of manuring effect (see below), which may have been subsequently propagated to pig collagen though the consumption of animal products.

Home-based management at Can Sadurní seems to be corroborated by other lines of evidence. Archaeobotanical and zooarchaeological analyses suggest that the site was used as a stall for sheep and goats (Saña et al., 2015). Moreover, organic residue analysis recently detected dairy products in Early Neolithic ceramic vessels from this site, suggesting that the cave may also have been used in dairy production (Debono Spiteri et al., 2016). Presumably the small number of pigs at Can Sadurní may have been kept in enclosed regime, and could have been foddered on a range of locally available sources, including animal products. Interestingly, the only specimen of wild boar analysed from Can Sadurní had a high $\delta^{15}N$ value, comparable with those of the pigs. Whether this indicates that wild boars may have been kept enclosed along with domesticated pigs, or if their natural diet also included several animal products, remains a matter of debate. However the number of specimens from Can Sadurní is too small to lead to conclusive interpretations.

Conversely, pigs from La Draga, cova del Frare and Serra de Mas Bonet had $\delta^{15}N$ values consistent with their respective local herbivores, which might be associated with a free-range system. Our results indicate that pigs were fed predominantly on plant products, which might indicate that they were free to roam in forested environments. However, the relatively elevated frequency of neonates at La Draga, where no bias is expected against adult specimens due to differential preservation processes (Saña et al., 2014), suggests that pigs were kept within the settlement and possibly managed at the household level (Antolín et al., 2014). If this was the case, their feeding management may have predominantly included plant products, perhaps by-products of crop production (e.g. cereals, pulses). Similar interpretations have been proposed for prehistoric pigs possibly raised at the household level but on a dominantly herbivorous diet (Balasse et al., 2016), and for modern pigs raised in traditional farming communities (Hadjikoumis, 2012). Two specimens from La Draga had remarkably high $\delta^{15}N$ values, perhaps indicating variability in husbandry regimes at the local scale. This could be due to selective feeding practices, for reasons that remain unclear for us, or variability of protein intake between households (e.g. Sykes, 2014). These two specimens form a distinctive isotopic group (Fig. 2), plotting along with one wild boar and one European badger, which may also indicate that some pigs were not local, but rather were raised elsewhere then brought to the site at a later stage. This seems to be supported by the large range of $\delta^{13}C$ values of local herbivores, which again could be tentatively associated with non-local animals. Moreover, shellfish and lithic raw material sourced from coastal areas were used by Neolithic groups at La Draga (Terradas et al., 2012). These independent lines of evidence suggest that La Draga was integrated within a regional trading network that may have involved circulation of livestock.

Recent studies suggest that pigs from La Draga were integrated within intensive mixed farming, where they would have had access to the fields for grazing on leftover crops while also manuring the plots (Antolín et al., 2014). Interestingly, domestic herbivores at La Draga were significantly ^{15}N enriched by 0.6‰ compared to the wild ones. This slight enrichment is also observed in the average $\delta^{15}N$ values of pigs, which is higher by 0.7‰ compared with the average values of the wild herbivores. However, the enrichment in ^{15}N is too low for a manuring effect if we consider the $\delta^{15}N$ values of manured crops in several Neolithic contexts in Europe (Fraser et al., 2011; Bogaard et al., 2013). This could, however, be due to the isotopic resolution not being adequate to resolve short-term feeding practices. Moreover, the effect of animal dung on plant $\delta^{15}N$ values is highly variable, and depends on, among other factors, the rate of manuring and the type of fertilizer (Fraser et al., 2011; Szpak, 2014). Furthermore, the increase in ^{15}N is not homogenous throughout the plant, and manured cereal straws may be depleted in ^{15}N relative to the grains (Bogaard et al., 2007, 2013). Legumes were also documented (though scarcely) at La Draga (Berrocal et al., in press), but these are typically ^{15}N depleted compared to cereal grains, and their $^{15}N/^{14}N$ only respond to a very high level of manuring (Bogaard et al., 2013). The isotope results of pigs from La Draga provide new insights into feeding management practices, but the scale of husbandry remains unclear. The same can be stated for cova del Frare and Serra de Mas Bonet, where the scarce archaeological information prevents conclusive interpretations to be drawn.

Our results indicate the coexistence of distinct foddering strategies among pig populations during the Early Neolithic in the NE Iberian Peninsula, but the scale of husbandry still remains elusive. The relative importance of pigs does not appear to be homogeneous among sites, but this does not seem to affect pig diet. However some variability was also observed in the size of specimens found at these sites. A large size variability indeed characterized pig populations in the Iberian Peninsula during the Neolithic, resulting from different selective environmental and social pressures (Navarrete & Saña, 2017). Stable isotope analysis on single amino acids from bone collagen may provide in the future additional complementary information on pig foddering strategies. This may be complemented with nitrogen isotope analysis of plant remains that are currently under investigation.

Determining the diet of domestic animals is also essential for developing appropriate isotopic baselines for interpreting human $\delta^{13}C$ and $\delta^{15}N$ values in order to derive paleodietary information. For example, relatively high $\delta^{15}N$ values were recently observed in Neolithic human individuals in this region (Fontanals-Coll et al., 2015, 2017) and were tentatively interpreted as the occasional consumption of freshwater fish. The isotopic data discussed in this work suggests that variability in pig foddering strategies provides an alternative explanation to freshwater fish consumption, assuming that pigs were a relevant source of animal protein to human diet.

Conclusion

In this study we analyzed bulk collagen carbon and nitrogen stable isotopes of pigs from six Early Neolithic sites in the northeastern Iberian Peninsula dated between ca. 5700 and 4200 cal BC. When compared with herbivores, we observed significant differences in pig $\delta^{15}N$ values between the sites that likely reflect variable foddering strategies. These differences may be indicative of variable management strategies, perhaps resulting from distinct adaptive responses to natural and/or social factors. In particular, a mainly herbivorous diet was detected in pig specimens from cova del Frare, La Draga and Serrat de Mas Bonet, which could reflect free-range or semi-free management systems. On the other hand, a higher consumption of animal protein could be postulated for pig specimens from Can Sadurní and Reina Amàlia-Caserna de Sant Pau, which in turn would reflect household-level regimes or the presence of pigs raised in enclosures. In summary, multiple factors may have contributed to the variability in foddering strategies among the earliest farmers in this area. This study offers new elements for discussing and opening new perspectives into early animal management strategies and the implications for understanding management strategies during the regional development of the Neolithic economy in the Iberian Peninsula.

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Table caption

Table 1. Conventional radiocarbon date along with calibrated radiocarbon ages using OxCal 4.2 software (IntCal13; Reimer et al., 2013).

Table 2. Results from isotopic analysis of faunal samples.

Figure caption

Figure 1. Location of the sites in the northeastern Iberian Peninsula.

Figure 2. Bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of animals from cova del Frare, Reina Amàlia-Caserna de Sant Pau, Can Sadurní, La Draga and Serra de Mas Bonet.

Figure 3A-B. δ^{13}C and δ^{15}N values of pigs (unfilled circle) corrected for the average δ^{13}C and δ^{15}N values of herbivores (Δ‰) for cova del Frare (CF), La Draga (DR), Reina Amàlia-Caserna de Sant Pau (RA-CSP) and Can Sadurní (CS). We also corrected the δ^{13}C and δ^{15}N values of herbivores for their average δ^{13}C and δ^{15}N values (filled circles) in order to show their isotopic variability.

Supplementary information

SI 1. Summary statistics for pig measurements from the sites in the northern Iberian Peninsula, Valencina de la Concepcion, Zambujal, Durrington Walls, La Draga, Reina Amàlia, Caserna de Sant Pau, cova del Frare and Can Sadurní. N = number of specimens, MIN = minimum, MAX = maximum, VAR = coefficient of variation. List of the measurements taken, according to von den Driesch, 1976.

SI 2. Pig measurements for spciemens selected for isotopic analysis from La Draga, Reina Amàlia, Caserna de Sant Pau, cova del Frare, Can Sadurní and Serra de Mas Bonet. List of the measurements taken according to von den Driesch, 1976.

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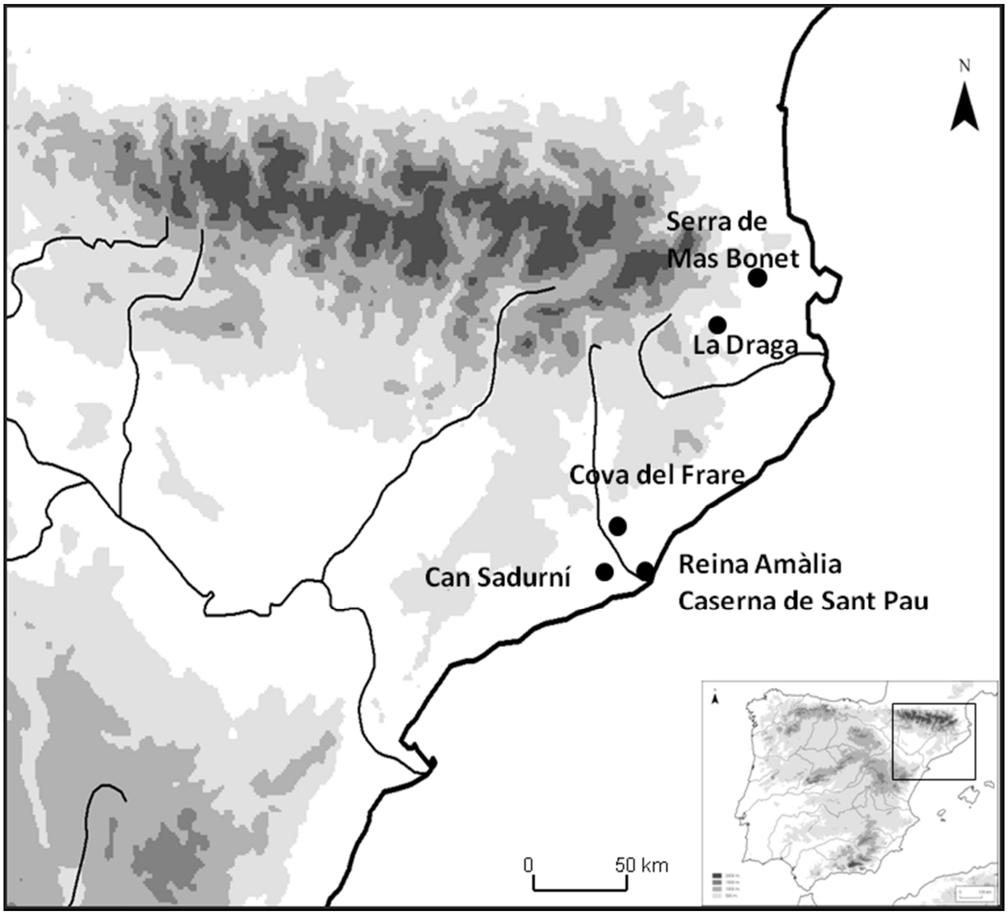


Location of the sites in the northeastern Iberian Peninsula.

64x58mm (300 x 300 DPI)

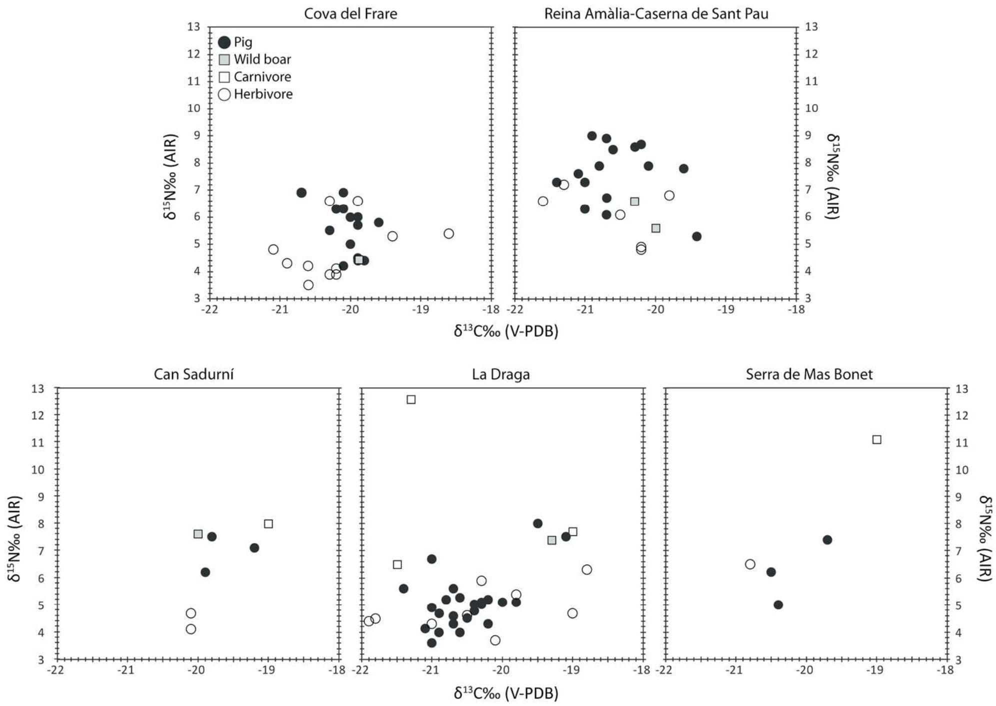
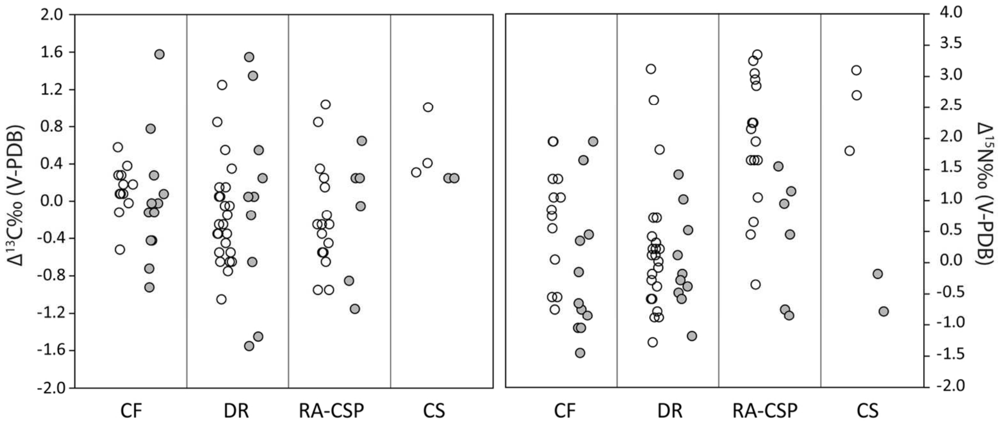


Figure 2. Bone collagen δ13C and δ15N values of animals from cova del Frare, Reina Amàlia-Caserna de Sant Pau, Can Sadurní, La Draga and Serra de Mas Bonet.
Figure 3A-B. δ13C and δ15N values of pigs (unfilled circle) corrected for the average δ13C and δ15N values of herbivores (Δ‰) for cova del Frare (CF), La Draga (DR), Reina Amàlia-Caserna de Sant Pau (RA-CSP) and Can Sadurní (CS). We also corrected the δ13C and δ15N values of herbivores for their average δ13C and δ15N values (filled circles) in order to show their isotopic variability.

155x108mm (300 x 300 DPI)



δ13C and δ15N values of pigs (unfilled circle) corrected for the average δ13C and δ15N values of herbivores (Δ‰) for cova del Frare (CF), La Draga (DR), Reina Amàlia-Caserna de Sant Pau (RA-CSP) and Can Sadurní (CS). We also corrected the δ13C and δ15N values of herbivores for their average δ13C and δ15N values (filled circles) in order to show their isotopic variability.

133x56mm (300 x 300 DPI)

Location	Level	^{14}C yr BP	Material	^{14}C yr cal BP (2σ)	^{14}C yr cal BC (2σ)	Reference
Gerona	-	-	Animal bone	-	4900-4600	Rosillo et al., 2010
Gerona	-	6010±70	Animal bone	7150-6670	5201-4721	Terradas et al., 2015
Barcelona	C6	6150±40	Animal bone	7165-6942	5216-4993	This study
Barcelona	C5	6020±40	Animal bone	6950-6770	5000-4820	Oms, 2014
Barcelona	I-II-III	5670±40	Animal bone	6560-6322	4611-4373	González et al., 2011
Barcelona	-	6290±50	Animal bone	7321-7025	5372-5076	Molist et al., 2008
Barcelona	10b/11	5540±40	Animal bone	6405-6284	4456-4335	Edo et al., 2011
Barcelona	17	6050±110	Charcoal	7240-6659	5291-4710	Blasco et al., 1999

Site	Specimens ID	Niv	Species ID	Skeleton part	%yield	%C	%N	$\delta^{13}C$(‰)	$\delta^{15}N$(‰)	C:N	LAB
Cova del Frare	**48**	C5	*Sus domesticus*	Maxilla	1.4	36	13	-20.1	6.3	3.2	UAB
Cova del Frare	**50**	C5	*Sus domesticus*	Maxilla	5.8	43	15	-20.0	6.0	3.3	UAB
Cova del Frare	**45**	C5	*Sus domesticus*	Mandible	6.7	43	15	-19.6	5.8	3.3	UAB
Cova del Frare	**67**	C5	*Sus domesticus*	Mandible	4.7	41	15	-19.9	6.0	3.2	UAB
Cova del Frare	**46**	C5	*Sus scrofa*	Mandible	1.3	31	11	-19.9	4.5	3.3	UAB
Cova del Frare	**68**	C5	*Sus domesticus*	Mandible	4.3	39	15	-20.7	6.9	3.0	UAB
Cova del Frare	**53**	C5	*Sus domesticus*	Maxilla	4.9	43	15	-20.0	5.0	3.3	UAB
Cova del Frare	**49**	C6	*Sus domesticus*	Maxilla	3.0	39	14	-19.8	4.4	3.3	UAB
Cova del Frare	**54**	C5	*Sus domesticus*	Maxilla	4.0	42	15	-20.1	6.9	3.3	UAB
Cova del Frare	**52**	C6	*Sus domesticus*	Maxilla	2.7	42	15	-20.2	6.3	3.3	UAB
Cova del Frare	**47**	C5	*Sus domesticus*	Mandible	1.7	42	14	-19.9	4.4	3.5	UAB
Cova del Frare	**51**	C6	*Sus domesticus*	Humerus	5.9	38	13	-20.1	4.2	3.4	UAB
Cova del Frare	**66**	C5	*Sus domesticus*	Humerus	4.9	42	15	-19.9	5.7	3.3	UAB
Cova del Frare	**36**	C6	*Sus domesticus*	Humerus	3.1	40	14	-20.3	5.5	3.3	UAB
Cova del Frare	**60**	C6	*Bos taurus*	Metatarsus	3.7	34	12	-19.4	5.3	3.3	UAB
Cova del Frare	**63**	C6	*Capra hircus*	Humerus	2.3	40	15	-20.1	6.9	3.1	UAB
Cova del Frare	**57**	C5	*Capra hircus*	Humerus	4.7	41	15	-20.3	3.9	3.2	UAB
Cova del Frare	**56**	C5	*Capra hircus*	Humerus	5.2	41	15	-20.6	4.2	3.2	UAB
Cova del Frare	**62**	C6	*Capra hircus*	Humerus	2.4	42	15	-20.6	3.5	3.3	UAB
Cova del Frare	**58**	C5	*Capra hircus*	Humerus	1.9	33	12	-20.3	6.6	3.2	UAB
Cova del Frare	**72**	C5	*Capra hircus*	Metacarpus	6.9	41	15	-20.2	4.1	3.2	UAB
Cova del Frare	**65**	C6	*Capreolus capreolus*	Metatarsus	3.2	34	13	-20.2	3.9	3.1	UAB
Cova del Frare	**55**	C5	*Cervus elephus*	Metatarsus	4.1	39	14	-18.6	5.4	3.3	UAB
Cova del Frare	**69**	C5	*Cervus elephus*	Tibia	4.1	39	15	-21.1	4.8	3.0	UAB
Cova del Frare	**61**	C6	*Ovis aries*	Humerus	4.3	40	15	-19.9	6.6	3.1	UAB
Cova del Frare	**73**	C5	*Ovis aries*	Tibia	5.7	41	15	-20.9	4.3	3.2	UAB
Caserna de Sant Pau	**99**	XV	*Sus domesticus*	Maxilla	1.4	32	11	-20.9	9.0	3.4	UAB

Caserna de Sant Pau	**94**	XXV	*Sus domesticus*	Mandible	1.7	40	14	-21.4	7.3	3.3	UAB
Caserna de Sant Pau	**82**	XXV	*Sus domesticus*	Humerus	1.1	36	12	-20.7	6.1	3.5	UAB
Caserna de Sant Pau	**93**	XVIII	*Sus domesticus*	Radius	1.2	37	14	-20.7	8.9	3.1	UAB
Caserna de Sant Pau	**86**	XVII	*Sus domesticus*	Tibia	1.6	43	16	-20.7	6.7	3.1	UAB
Caserna de Sant Pau	**92**	XXIII	*Capra hircus*	Humerus	2.5	42	16	-19.8	6.8	3.1	UAB
Caserna de Sant Pau	**90**	XII	*Bos taurus*	Metacarpus	2.4	40	14	-21.6	6.6	3.3	UAB
Caserna de Sant Pau	**88**	XVII	*Ovis aries*	Metatarsus	2.1	39	14	-21.3	7.2	3.3	UAB
Can Sadurní	**44**	10	*Sus domesticus*	Mandible	1.4	33	12	-19.2	7.1	3.2	UAB
Can Sadurní	**42**	10	*Sus domesticus*	Mandible	2.7	37	13	-19.8	7.5	3.3	UAB
Can Sadurní	**43**	11b	*Sus domesticus*	Mandible	1.9	40	14	-19.9	6.2	3.3	UAB
Can Sadurní	**122**	17	*Sus scrofa*	Phalanx	1.0	37	13	-20.0	7.6	3.3	UAB
Can Sadurní	**126**	17	*Capra hircus*	Mandible	0.4	31	11	-20.1	4.7	3.3	UAB
Can Sadurní	**129**	10	*Bos taurus*	Metatarsus	2.7	35	13	-20.1	4.1	3.1	UAB
Can Sadurní	**132**	10	*Canis familiaris*	Metatarsus	2.3	43	16	-19.0	8.0	3.1	UAB
La Draga	**2**	B	*Sus domesticus*	Humerus	3.0	43	16	-21.1	4.1	3.1	UAB
La Draga	**16**	B	*Sus domesticus*	Mandible	7.2	42	15	-20.6	4.0	3.3	UAB
La Draga	**20**	B	*Sus domesticus*	Maxilla	9.4	42	14	-20.5	4.5	3.5	UAB
La Draga	**10**	B	*Sus domesticus*	Tibia	4.3	42	15	-20.0	5.1	3.3	UAB
La Draga	**18**	B	*Sus domesticus*	Mandible	2.9	42	14	-20.7	4.3	3.5	UAB
La Draga	**1**	B	*Sus domesticus*	Humerus	4.1	42	15	-20.7	4.6	3.3	UAB
La Draga	**5**	B	*Sus domesticus*	Humerus	1.3	36	12	-21.4	5.6	3.5	UAB
La Draga	**7**	A	*Sus domesticus*	Radius	5.6	39	14	-19.1	7.5	3.3	UAB
La Draga	**D-26**	A	*Sus domesticus*	Tibia	3.3	41	15	-20.3	5.1	3.2	York
La Draga	**21**	B	*Sus domesticus*	Maxilla	4.9	42	14	-20.8	5.2	3.5	UAB
La Draga	**17**	B	*Sus domesticus*	Mandible	5.1	43	15	-20.9	4.0	3.3	UAB
La Draga	**15**	B	*Sus domesticus*	Tibia	10.6	44	15	-21.0	4.9	3.4	UAB
La Draga	**12**	B	*Sus domesticus*	Radius	9.7	42	15	-21.0	6.7	3.3	UAB
La Draga	**11**	B	*Sus domesticus*	Radius	5.1	42	15	-20.4	5.0	3.3	UAB

La Draga	**8**	B	*Sus domesticus*	Radius	3.1	42	15	-20.6	5.3	3.3	UAB
La Draga	**9**	B	*Sus domesticus*	Tibia	2.3	42	15	-20.9	4.7	3.3	UAB
La Draga	**19**	B	*Sus domesticus*	Maxilla	6.2	43	14	-19.8	5.1	3.6	UAB
La Draga	**4**	A	*Sus domesticus*	Humerus	1.2	40	13	-21.0	3.6	3.6	UAB
La Draga	**28**	D	*Sus domesticus*	Humerus	1.1	37	12	-20.7	5.6	3.6	UAB
La Draga	**26**	D	*Sus domesticus*	Tibia	3.8	42	15	-20.2	4.3	3.3	UAB
La Draga	**29**	B	*Sus domesticus*	Radius	6.7	43	15	-20.4	4.8	3.3	UAB
La Draga	**27**	B	*Sus domesticus*	Humerus	4.2	42	15	-20.3	5.0	3.3	UAB
La Draga	**D-18**	B	*Sus domesticus*	Humerus	6.9	42	15	-20.2	5.2	3.3	York
La Draga	**D-34**	B	*Meles meles*	Humerus	1.2	35	12	-21.3	12.6	3.5	York
La Draga	**165**	B	*Bos taurus*	Humerus	7.6	36	13	-18.8	6.3	3.2	UAB
La Draga	**163**	B	*Bos taurus*	Tibia	2.3	36	13	-19.8	5.4	3.2	UAB
La Draga	**D-28**	B	*Canis familiaris*	Tibia	6.6	41	15	-21.5	6.5	3.2	York
La Draga	**159**	B	*Capra hircus*	Humerus	2.8	38	13	-20.3	5.9	3.4	UAB
La Draga	**10A**	B	*Capra pyrenaica*	Humerus	5.7	42	15	-21.8	4.5	3.3	UAB
La Draga	**20A**	B	*Capra pyrenaica*	Humerus	3.2	35	12	-20.1	3.7	3.4	UAB
La Draga	**13A**	B	*Capra pyrenaica*	Metacarpus	9.1	36	12	-20.3	5.0	3.5	UAB
La Draga	**D-10**	B	*Capreolus capreolus*	Humerus	4.2	29	10	-21.9	4.4	3.4	York
La Draga	**D-6**	B	*Cervus elephus*	Phalanx	2.1	45	15	-21.0	4.3	3.5	York
La Draga	**D-11**	B	*Meles meles*	Humerus	7.8	47	17	-19.0	7.7	3.2	York
La Draga	**162**	B	*Ovis aries*	Tibia	1.0	34	12	-19.0	4.7	3.3	UAB
La Draga	**160**	B	*Ovis aries*	Radius	2.2	38	13	-20.5	4.6	3.4	UAB
Reina Amàlia	**137**	FIII	*Sus scrofa*	Humerus	0.7	29	10	-19.3	7.4	3.4	UAB
Reina Amàlia	**136**	FII	*Sus domesticus*	Humerus	1.7	34	13	-19.5	8.0	3.1	UAB
Reina Amàlia	**149**	FII	*Sus domesticus*	Mandible	1.4	34	13	-20.3	8.6	3.1	UAB
Reina Amàlia	**140**	FI	*Sus domesticus*	Radius	1.8	42	16	-19.6	7.8	3.1	UAB
Reina Amàlia	**143**	FI	*Sus domesticus*	Maxilla	1.2	32	12	-20.1	7.9	3.1	UAB
Reina Amàlia	**147**	FI	*Sus domesticus*	Mandible	1.0	35	13	-21.0	7.3	3.1	UAB

Reina Amàlia	**139**	FI	*Sus domesticus*	Humerus	1.6	34	13	-20.8	7.9	3.1	UAB
Reina Amàlia	**138**	FII	*Sus domesticus*	Humerus	1.3	35	13	-19.4	5.3	3.1	UAB
Reina Amàlia	**145**	FII	*Sus domesticus*	Mandible	1.6	36	13	-20.2	8.7	3.2	UAB
Reina Amàlia	**146**	FI	*Sus domesticus*	Mandible	0.7	33	11	-21.1	7.6	3.5	UAB
Reina Amàlia	**41**	FI	*Sus domesticus*	Mandible	1.3	40	14	-21.0	6.3	3.3	UAB
Reina Amàlia	**40**	FI	*Sus domesticus*	Mandible	1.9	42	15	-20.6	8.5	3.3	UAB
Reina Amàlia	**144**	FI	*Sus domesticus*	Mandible	1.5	40	14	-21.4	7.3	3.3	UAB
Reina Amàlia	**142**	FI	*Sus scrofa*	Metatarsus	1.3	36	13	-20.3	6.6	3.2	UAB
Reina Amàlia	**141**	FII	*Sus scrofa*	Metatarsus	1.1	36	14	-20.0	5.6	3.0	UAB
Reina Amàlia	**150**	FII	*Bos taurus*	Metatarsus	1.3	40	15	-20.2	4.9	3.1	UAB
Reina Amàlia	**151**	FIV	*Bos taurus*	Tibia	1.0	31	11	-20.5	6.1	3.3	UAB
Reina Amàlia	**155**	FII	*Capra pyrenaica*	Radius	1.1	38	14	-20.2	4.8	3.2	UAB
Serra de Mas Bonet	**181**	-	*Sus domesticus*	Tibia	1.5	32	11	-20.4	5.0	3.4	UAB
Serra de Mas Bonet	**180**	-	*Sus domesticus*	Metacarpus	1.6	37	13	-19.7	7.4	3.3	UAB
Serra de Mas Bonet	**182**	-	*Sus domesticus*	Phalanx	1.7	37	12	-20.5	6.2	3.6	UAB
Serra de Mas Bonet	**171**	-	*Canis familiaris*	Mandible	0.6	36	12	-19.0	11.1	3.5	UAB
Serra de Mas Bonet	**174**	-	*Capra hircus*	Humerus	0.6	27	10	-20.8	6.5	3.2	UAB