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RESEARCH

Choose what suits you best: reproductive patterns and livestock management in the Iron Age Iberian Peninsula (3rd c. BC)

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Abstract
Isotopic analyses have proven to be an essential tool for obtaining more comprehensive and precise knowledge about past livestock strategies. Nevertheless, biogeochemical data for the Iron Age and, in particular, for the Iberian Peninsula are still very scarce. This study aims to provide a first and pivotal glimpse of sheep reproductive strategies adopted by north-eastern Iberian societies during the Middle and Late Iron Age, a period in which a process of urbanisation and agricultural expansion took place. Birth seasonality and the duration of the lambing period are here investigated through sequential oxygen isotope analyses performed on sheep's second and third lower molars from four relevant Catalan sites (Mas Castellar de Pontós, Tossal de Baltarga, Sant Esteve d'Olius, Turó de la Rovira). These are contemporary (third century BC) and are located in different ecological and cultural areas. Results display diversified sheep reproductive patterns and distinct demographical management in the four settlements, with manipulations both on the season and on the duration of the lambing period. Thus, we propose that herd management and exploitation were determined by specific economic demands and the social organisation and environmental conditions of each area. Therefore, through this biogeochemical approach, we have been able to demonstrate that the resources, knowledge and time involved in the organisation of sheep husbandry were much more complex and planned than classical zooarchaeological studies have so far documented, highlighting the importance of livestock farming as a key activity in the economy of the Iron Age Iberian communities.

Keywords Stable oxygen isotopes · Birth seasonality · Lambing period · Animal husbandry strategies · Middle-Late Iron Age · NE Iberian Peninsula

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Introduction and research objectives

Historical context and aim of the research project

Since the Middle Iron Age and until the Roman conquest, the north-eastern (NE) Iberian societies were characterised by a proto-state structure, strongly hierarchical and arranged into different centralised political entities (Gracia 2005; Sanmartí 2014, 2021). In this context, a wide set of interconnected open-air settlements with specific functions emerged: i.e. fortified centres, rural establishments, small villages and silo fields (Gracia 2005; Sanmartí 2014, 2021). All of them were structured around the so-called first-order cities, central nuclei whose main function was the control and centralisation of agricultural production (Asensio et al. 1998; Bouso et al. 2000; Sanmartí 2004, 2014; Sanmartí et al. 2019). These communities developed a predominantly local agricultural economy devoted to self-sufficiency where cereal

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surplus represented the main exchange product (Asensio et al. 2003a; Asensio 2013; Prats et al. 2020).

Livestock husbandry was another key activity among the subsistence strategies of these communities. This NE Iberian husbandry was mostly specialised in caprines, with a predominance of sheep (Franquesa et al. 2000; Perez et al. 2007; Colominas 2008a; Colominas et al. 2011), probably due to its capacity to produce a broad variety of products (i.e. meat, milk, wool, manure) and for its great adaptability to different environmental constraints (Albizuri and Nadal 1999; Rasali et al. 2006; Colominas 2006; Perez et al. 2007). The adoption of diversified and selective livestock strategies aimed at self-sufficiency and suited to the necessities of each settlement has been demonstrated by the results of zooarchaeological studies carried out so far (Albizuri and Nadal 1999; Franquesa et al. 2000; Colominas 2008b, 2013a; Colominas et al. 2019; Nieto Espinet et al. 2021). However, despite this self-sufficiency, a general ever-increasing tendency towards a specialisation in secondary products is also detected (Franquesa et al. 2000; Colominas 2006; Colominas et al. 2011). In this scenario, obtaining a more comprehensive and, at the same time, more precise knowledge about the different livestock strategies adopted by Iberian Iron Age societies is necessary.

In order to achieve this, in this study, we apply a biogeochemical approach investigating sheep seasonal reproductive strategies in four Middle/Late Iron Age settlements located in the northeast of the Iberian Peninsula (present-day Catalonia). Season and seasonality of sheep birth are examined to explain how Iberian sheepherders managed control of reproductive cycles. Our study will allow detecting if different reproduction patterns within the same settlement exist and if this key-diagnostic aspect of sheep management was performed differently at each site. Evidence of those practices is crucial to identify how pastoralist labour was managed and how the production of meat, milk and other products was organised (Balasse et al. 2003). This data provides valuable information about livestock management and exploitation strategies developed by the Iberian communities. Since biogeochemical data are still very scarce for protohistoric periods and, in particular, for the Iberian Peninsula, the present study also aims to begin to fill the lack of stable isotope results about the Iron Age Iberian societies.

Seasonal reproductive patterns inferred by sequential $\delta^{18}O$ values

Biogeochemical data and stable isotope analyses have proven to be fundamental tools for complementing and enriching traditional zooarchaeological studies reconstructing past husbandry strategies. With a seasonal time-scale resolution, sequential or dental series of oxygen isotope values from sheep molars enamel can provide innovative life history data about past herds (Balasse 2002). Once mineralised, tooth enamel does not turn over and reflects the isotopic signal registered during its formation. The oxygen isotope composition measured in the tooth enamel mineral fraction (i.e. bioapatite compound) is mainly derived from ingested water and plants consumption (Longinelli 1984; Luz et al. 1984), and these isotopic signatures are well-related to the meteoric water and temperature, which, in temperate latitudes, vary according to the seasonal changes. At mid and high latitudes, higher $\delta^{18}O$ values reflect the warmer season, whilst the coldest one is recorded by lower $\delta^{18}O$ values (Gat 1980). Through the $\delta^{18}O$ sequences recorded in each tooth crown, the seasonality and reproductive dynamics of the sampled sheep specimens are investigated using the position of the maximum and minimum seasonal climatic events along the tooth crown.

The season of birth of archaeological sheep specimens can also be inferred using sequential series of $\delta^{18}O$ values. Similar sinusoidal variations of warm and cold episodes between different sampled individuals would indicate synchronised births, whilst divergences may indicate different birth seasons. However, dental crown height may vary between individuals (Balasse et al. 2012), affecting sequential $\delta^{18}O$ series and inter-individual variability. Therefore, in order to compare the placement of oxygen sequences between individuals, it is necessary to eliminate the bias associated with tooth size variability and normalise the distances (Knockaert 2017). Using the method proposed by Balasse and colleagues (2012), it is possible to model the sequences and to describe and compare the data obtained objectively (Tornero et al. 2013). Finally, to infer an individual's season of birth, it is necessary to consider the delay in enamel mineralisation, which affects the recording of the isotopic signal in the crown (Balasse et al. 2012). For this reason, it is indispensable to use modern sheep populations with known season of birth. These references make it possible to place the birth seasons of archaeological individuals within an annual calendar and hence understand the distribution of births within past societies' herds (Knockaert 2017). Reference data are currently available for both M_2 and M_3; a higher inter-individual variability in the timing of M_3 formation has been observed, resulting in a lower resolution at the time of defining the birth calendar. In this study, the reliability of M_3s for defining the birth calendar of archaeological individuals is tested.

Season and seasonality of sheep birth have been investigated in zooarchaeological studies with increasing interest during the last decade. Knowing the timing and the length of the caprine lambing season during the year is indeed essential for fully interpreting the ancient pastoral societies' practices (Balasse et al. 2017; Knockaert 2017). So far, a significant focus has been placed on archaeological sites in Europe and the Near East, dating from the 6th to the

3rd millennium B.C. (Tornero 2011; Tornero et al. 2016; Hadjikoumis et al. 2019), to shed light on domestication's origin and early development. These studies have shown that human intervention in sheep populations favoured a prolongation in the duration of the birth period and, consequently, an extension of the period of sexual activity (Balasse et al. 2017). Furthermore, it has been possible to trace the earliest evidence of out-of-season births (during autumn) in the western Mediterranean, at the two Early Neolithic sites of Taï and Gazel, in Southern France (Tornero et al. 2020); this demonstrated that the capability of de-seasoning births was already present, at least, in the second half of the 6th millennium BC in the Western Mediterranean.

Sites

Samples selected proceed from archaeological sites with contemporaneous and well-dated occupations along the third century BC. All sites are open-air settlements located in distinct ecological and cultural areas within the northeast of the Iberian Peninsula (Fig. 1). Mas Castellar de Pontós is located on a fertile plain in the northern pre-coastal area, in the territory of Indigeti; at higher altitude is the Ceretan settlement of Tossal de Baltarga, on the Cerdanya plain; moving inland there is Sant Esteve d'Olius in the Pre-Pyrenees area, on the fertile Lacetan agricultural plain; and finally, close to the central Mediterranean coast, the Laietan site of Turó de la Rovira extends over the Barcelona plain. In all settlements, agriculture has been traditionally described as the main economic activity within subsistence strategies, documenting management, production, storage and distribution of agricultural surplus (Pons et al. 2010; Morera 2017; Asensio et al. 2008). In the Iberian period, crops in the north-eastern Iberian Peninsula were dominated by wheat (*Triticum aestivum/durum*) and barley (*Hordeum vulgare*) and, secondarily, by millet (*Panicum miliaceum*) and leguminous plants (*Lens culinaris*, *Pisum sativum*, *Vicia faba*) suggesting the use of rotation cycles in the cultivations (Alonso 2000; Riera et al. 2020).

Mas Castellar de Pontós is located on the Empordà plain (Girona, highest altitude: 154 m. a.s.l.; Fig. 2), approximately 17 km equidistant from the Greek colonies of *Rhode* and *Emporion*. Being located on a promontory between two waterways, a tributary of the Muga and the river Fluvià, and close to the coast makes it a strategic point of communication between the coast and the interior, as well as between the two Greek colonies and the indigenous inhabitants (Pons et al. 2010). Along with the geographical factor, the humid and mild climate favoured the development of an important economic centre with a rural focus throughout the Iron Age (Pons et al. 2010). Human occupation covers a wide chronological frame, between the end of the seventh century and the beginning of the second century BC (Pons et al. 2010; Adroher and Pons 2002). The so-called rural establishment, a specialised agricultural settlement, was occupied between 250 and 180 BC. Associated with the rural establishment was an extensive silo field (Pons et al. 2010). Managed by a rural aristocracy, the settlement was an important commercial enclave for cereal production and a major reserve centre for the entire *Emporion* area (Fuertes et al. 2002; Bouso et al. 2000). Carpological data attest to the presence of both winter (wheat and emmer) and spring (millet, foxtail millet, barley, oats) crops, combined, in minor quantities, with the cultivation of legumes (pea, lentil) and grapes (Canal 2000, 2002). Production probably involved a variety

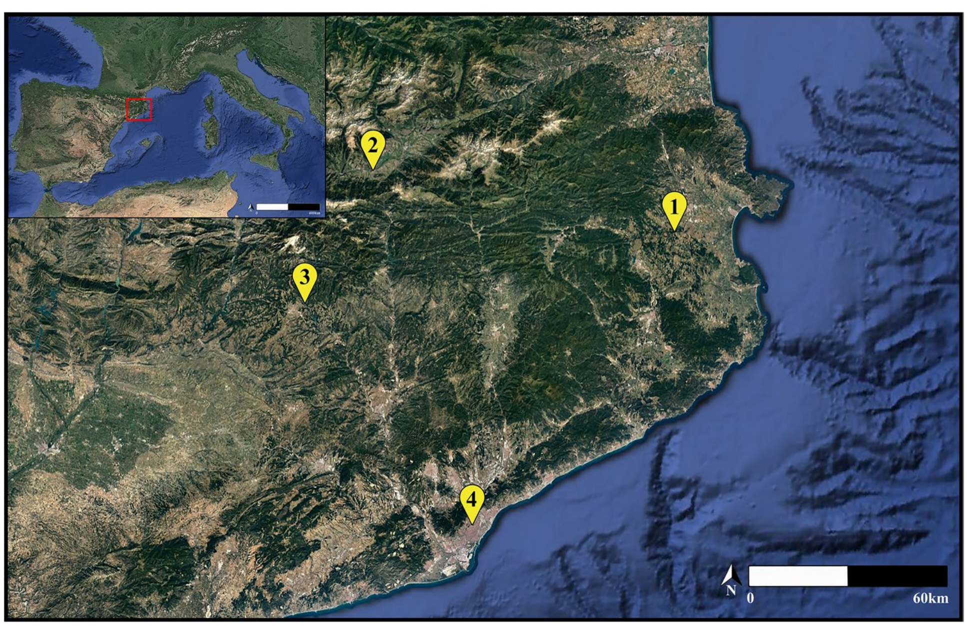

Fig. 1 Location of the four archaeological sites included in this study: (1) Mas Castellar de Pontós, (2) Tossal de Baltarga, (3) Sant Esteve d'Olius and (4) Turó de la Rovira (Google Earth Pro modified)

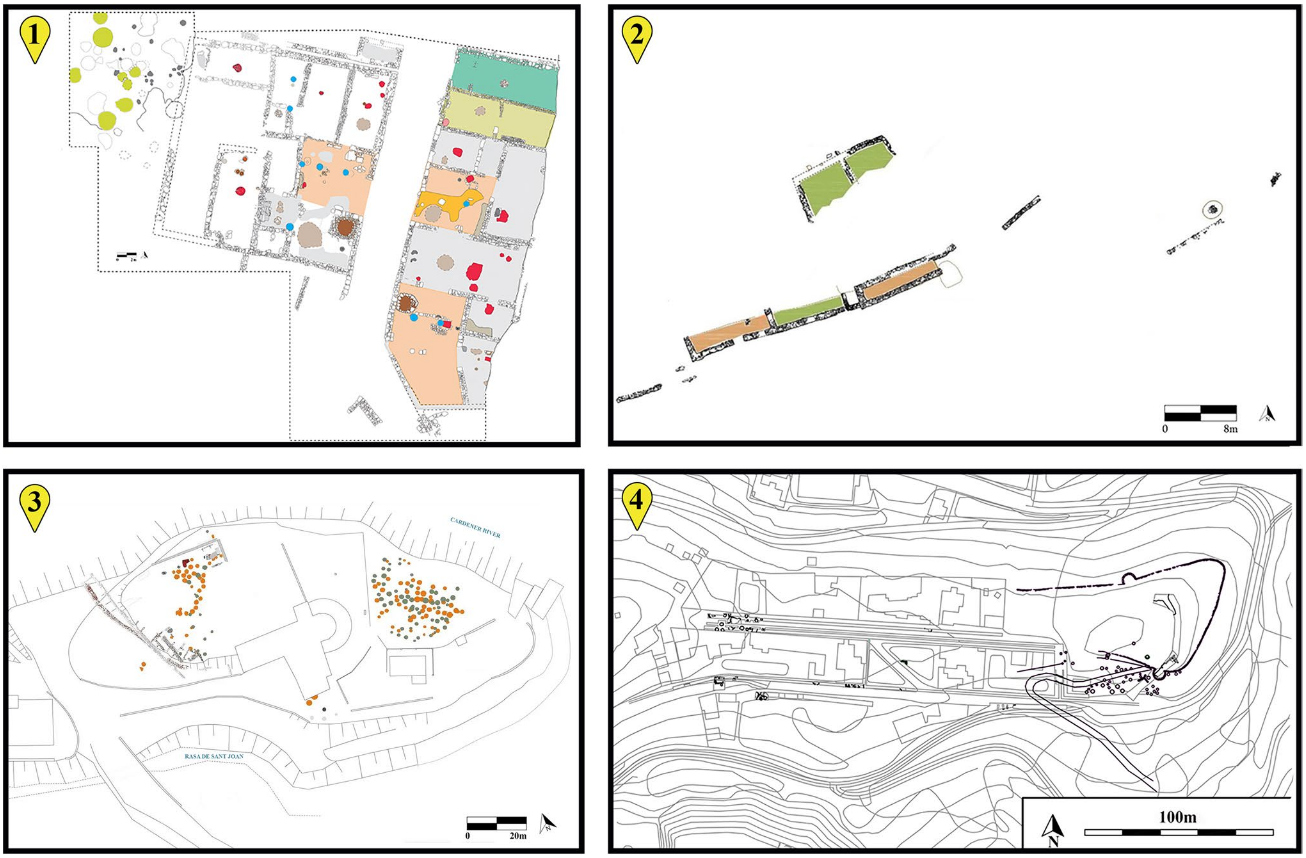

Fig. 2 Plans of the four archaeological sites: (1) Mas Castellar de Pontós (Garcia-Dalmau C., modified), (2) Tossal de Baltarga (Oller et al. 2021, modified), (3) Sant Esteve d'Olius (Morer de Llorens et al. 2016, modified) and (4) Turó de la Rovira (Giner Iranzo D., modified)

of crop management strategies, including both rotation systems (biennial and triennial) and the joint sowing of different species, such as foxtail millet and barley (Alonso 2000; Canal 2000).

The site of Tossal de Baltarga (Bellver de Cerdanya, 1166 m. a.s.l.; Fig. 2) is a high mountain settlement in the eastern Catalan Pyrenees, with a territorial control purpose of the routes crossing this area. Indeed, its position on the top of a hill allowed control over the land route and the crossing of the river Segre (Colominas et al. in press). Chronologically, it revealed three different phases, from the Late Bronze Age to the Republican Roman period (Morera 2017). During the Iberian phase (fourth to third century BC), the settlement is characterised by several residential and working buildings (Morera 2017; Colominas et al. in press). At the end of the third century BC, the site, with a certain social and economic relevance within the Ceretan population, was violently destroyed by fire (Morera 2017). The albeit limited carpological data from one of the buildings attest to the presence of barley, wheat, millet and einkorn (Colominas et al. in press). Large ceramic containers and concentrations of wheat grains were recovered from another building of the settlement, indicating a probable storage function (Olesti et al. 2018). Indeed, during the Iberian period, there was an increase in agricultural production in the Cerdanya plain, favoured by the generally dry climate but with abundant water sources (Morera 2017; Olesti and Mercadal 2017).

Sant Esteve d'Olius (Solsonès, 664 m a.s.l.; Fig. 2) is a village in the inland of the Catalan region. It is placed on the highest point of a small promontory, bordered by the river Cardener, the main communication way to the coast (Asensio et al. 2003b). The Iberian phase (3rd c. BC) is characterised by a fortified settlement specialised in the storage and management of cereal surpluses, with silo fields and residential buildings (Asensio et al. 2003b; Chorén and Calduch 2006; López 2009). The larger extension of silo fields compared to habitat structures reveals the prominence of agricultural activities in the settlement, favoured by the extension of the fertile plain irrigated by the river Cardener (Asensio et al. 2008). These types of strategic nuclei specialised in cereal storage are well known along the Iberian coastal areas, whilst they are exceptional in the interior, as in the case of Sant Esteve d'Olius (López 2009). The archaeobotanical data from the silos revealed a large quantity of barley remains and, in considerably minor quantities, wheat and emmer and traces of leguminous plants (pea and lentil). In general, the most represented are winter cereals, with a monospecific concentration of barley (López 2009).

The fortified settlement of Turó de la Rovira (mid-third century BC to late third/early second century BC) occupies the top of the homonymous plain situated in Barcelona (Barcelonès, 262 m. a.s.l.; Fig. 2; Colominas i Roca 1954; Giner 2018). Delimited by a wall, it is associated with a moat on the south-eastern side, two silo fields concentrated on the two sides of the village, and residential buildings on the southern slope (Giner 2018). The settlement has been interpreted as a second-order village of the Laietan territory, with a dominant position over neighbouring minor centres (Giner 2018). The environment was open and deforested, probably due to the presence of cultivated fields all around (Riera et al. 2020). Carpological data show agriculture with a predominance of wheat and barley and the presence of millet and, in minor quantities, legumes, grapes and figs (Riera et al. 2020).

Material and methods

Materials

A total number of 31 lower molars (18 second molars and 13 third molars) of 22 sheep (*Ovis aries*, Linnaeus, 1758) from four different archaeological sites were selected and analysed for this study. Ten second molars and seven third molars were extracted from mandibles, whilst all the others were isolated teeth. All selected molars present completely or almost fully formed crowns and early wear stages. Five second molars (MC *Ovis* 11144, MC *Ovis* 12023, MC *Ovis* 20102, MC *Ovis* 20160, MC *Ovis* 20165) and three third molars (MC *Ovis* 11132, MC *Ovis* 11134, MC *Ovis* 11138) here included were already used for analysis in a preliminary study (Messana et al. in press). Descriptive information (side, wear stage and estimated age of death) about the teeth selected for this study is presented in Table 1.

Methods

After cleaning the selected teeth surface by abrasion with a tungsten drill, enamel bands were sequentially sampled using a diamond bit. Sampling was performed on the buccal side, on the posterior lobe of M_2 and on the middle lobe of M_3. All the samples were taken at 1–2 mm intervals along the whole crown height, starting from the apex. Positions of sample bands were recorded in mm from the enamel-root junction (ERJ).

Between 10 and 20 samples per tooth were sampled, resulting in a total number of 473 samples. Powdered enamel samples (weighing between 2.5 and 13.7 mg) were chemically treated at the Biomolecular Laboratory of the Institut Català

Table 1 Sheep (ID), sampled teeth and estimated age of death of sampled specimens from the four archaeological sites included in this study: Mas Castellar de Pontós (MC), Tossal de Baltarga (BTB), Sant Esteve d'Olius (O) and Turó de la Rovira (TR). Side (*L*, left; *R*, right); wear stages, according to S. Payne (1973); *na*, no analysed. Estimated age of death following criteria and codes from Payne (1973)

Site	Sheep ID	Side	M_2		M_3	
			Wear stage	Age estimation	Wear stage	Age estimation
MC	11144	L	F	2–6 years	na	na
	12023	L	E	2–3 years	na	na
	20102	L	E	2–3 years	na	na
	20160	R	E	2–3 years	F	3–4 years
	20165	R	F	3–4 years	F	3–4 years
	11132	R	na	na	G	4–6 years
	11134	L	na	na	G	4–6 years
	11138	L	na	na	G	4–6 years
BTB	3249	R	E	2–3 years	na	na
	3270	R	F	3–4 years	F	3–4 years
	3271	L	D	21–24 months	na	na
	3031	L	na	na	F	3–4 years
O	174	L	E	2–3 years	na	na
	205	R	E	2–3 years	E	2–3 years
	318	R	G	4–5 years	G	4–5 years
	348	R	F	4–6 years	na	na
	478	L	E	2–3 years	E	2–3 years
	482	R	F	4–6 years	na	na
	484	R	F	4–6 years	na	na
TR	725	R	F	3–4 years	F	3–4 years
	763	L	F	3–4 years	F	3–4 years
	831	L	E	2–3 years	E	2–3 years

de Paleoecologia Humana i Evolució Social (IPHES-CERCA), following the protocol described in Balasse et al. (2002) and modified by Tornero et al. (2013). Samples were treated to eliminate contamination from exogenous carbonates (4 h in 0.1 M acetic acid (CH_3COOH); 0.1 ml solution/mg of sample), rinsed several times in distilled water and dried in an oven at 70 °C for 48 h.

Treated samples were measured using an automated carbonate preparation device (KIEL-III) interfaced to a Finnigan MAT 252 isotope ratio mass spectrometer (IRMS) at the Environmental Isotope Laboratory (Dept. of Geosciences), University of Arizona (USA), with scientific supervision from Dr. David Dettman. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70 °C. The accuracy and precision of measurements were checked and calibrated using NBS-19 and NBS-18 international standards. The mean analytical precision within each run and from replicate measurements of standards during analysis varies ±0.1‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$ (1 sigma). Isotope composition is reported in δ notation and expressed per mil (‰), in agreement with the corrections from standard V-PDB (Vienna-Pee Dee Belemnite) oxygen values.

Seasonal reproduction patterns were assessed following Balasse et al. 2003, 2012, and Tornero et al. 2013. In order to quantify the inter-individual variability in tooth size and to define the position of the maximum $\delta^{18}O$ value in the tooth crown (x_0/X), the $\delta^{18}O$ sequences were modelled using the equation described by Balasse et al. 2012, based on a cosine function. The model includes four parameters for M_2 modelling: the period of the cycle (X), expressed in mm and corresponding to the length of tooth crown potentially formed over a year; the amplitude of the isotopic signal (A), expressed in ‰; the delay (x_0) expressed in mm, corresponding to the position in tooth crown where the $\delta^{18}O$ has his maximum value; and the mean (M), expressed in ‰. For the modelling of M_3, four more parameters are added: the slope of the mean (p), expressed in mm; the signal attenuation (x_A) and the lateral shift (x_B) of the amplitude, both expressed in mm; the gradation of the period (b). As a consequence of the addition of parameter b, the normalised period for M_3 is given by x_0/X_{real}.

As the inter-variability in (x_0/X) reflects the variability in the birth season, this latter is estimated by comparison with data from modern sheep populations with the known date of birth. These reference data included individuals from Blaise and Balasse 2011, Balasse et al. 2012, Balasse et al. 2017, Balasse et al. 2020, Balasse et al. 2023 and Tornero et al. 2018.

Results

Oxygen isotope ratios

Results of the intra-tooth sequences of $\delta^{18}O$ values are summarised in Table 2 and comprehensively presented in Table S1 and Figure S1. The mean $\delta^{18}O$ value from all samples is 0.4 ± 1.6‰, ranging from 2.6 to −4.6‰. The mean $\delta^{18}O$ value within each specimen varies from 1.6 to −2.9‰, maximum values range from 2.6 to −1‰, minimum values range from 1‰ to −4.6‰ and the amplitude varies between 1.1 and 6‰.

Modelling of sequential $\delta^{18}O$ series

The results of the modelling of oxygen sequences are presented in Table S2 for the M_2 and in Table S3 for the M_3.

Oxygen sequences obtained in the M_2 could be all modelled except for the tooth O M2 348. Normalised results

Table 2 Summarised isotopic results ($\delta^{18}O$ values) in bioapatite samples from archaeological lower second (M_2) and third (M_3) sheep molars: mean, range, maximum (max) and minimum (min) isotopic values

Teeth	n	$\delta^{18}O_{V\text{-}PDB‰}$			
		Mean	Range	Max	Min
MC M2 11144	16	0.2	2.8	1.8	−1
MC M2 12023	19	−0.6	3.9	1.6	−2.3
MC M2 20102	14	1.6	1.1	2.1	1
MC M2 20160	13	0	4.1	2.2	−1.9
MC M2 20165	14	1	3.2	2.6	−0.6
MC M3 11132	14	0	2.3	1	−1.2
MC M3 11134	13	−0.1	2.8	1.2	1.5
MC M3 11138	17	0.2	2.7	1.4	−1.3
MC M3 20160	15	−0.6	2.9	0.5	−2.4
MC M3 20165	15	−0.3	2.6	0.9	−1.6
BTB M2 3249	16	−1.8	6	1.4	−4.6
BTB M2 3270	10	−0.6	3.9	0.9	−3
BTB M2 3271	13	−2.2	5.1	0.6	−4.5
BTB M3 3031	16	−1.3	4.6	1.1	−3.5
BTB M3 3270	12	−2	7	3.4	−3.6
O M2 174	18	−1.1	4.2	1	−3.2
O M2 205	15	−2.9	3.3	−0,8	−4.1
O M2 318	13	−1	3.4	0,3	−3
O M2 348	15	−2	2.9	−1	−3.9
O M2 478	16	−0.8	3.9	0.9	−3
O M2 482	16	−1.3	4	0.8	−3.2
O M2 484	14	−2.3	2.9	−0.7	−3.6
O M3 205	19	0.2	4	2.5	−1.6
O M3 318	20	−0.6	4.3	1.9	−2.4
O M3 478	14	0	5.2	2.1	−3.1
TR M2 725	18	0.6	2.2	1.9	−0.4
TR M2 763	17	0.9	2.6	2.2	−0.4
TR M2 831	17	0.9	2.3	2.4	0.1
TR M3 725	16	0.8	2	1.9	−0.1
TR M3 763	15	1.3	2.5	2.6	0.1
TR M3 831	13	0.6	2.4	1.4	−1

(x_0/X) for the M_2 are presented in Fig. 3. In Mas Castellar de Pontós, M_2 specimens show an x_0/X ratio that varies between 0.19 and 0.80, indicating a wide distribution of births over the annual cycle. Indeed, the results suggest that lambing occurred from autumn to the late spring. For sheep born in autumn (MC M2 20102, MC M2 20160, MC M2 20165), the duration of the lambing period can be estimated to be just over a month (0.10 years or 1.19 months); whilst for sheep born in spring (MC M2 11144, MC M2 12023), the duration of the lambing period can be estimated to 3 months (0.24 years or 2.93 months).

At Tossal de Baltarga, the M_2 x_0/X ratio varies between 0.08 and 0.28, with a duration of the lambing period of two and a half months (0.20 years or 2.42 months) and births occurred during late winter and spring seasons.

The M_2s from Sant Esteve d'Olius, with an x_0/X ratio between 0.06 and 0.48, show a wide lambing season of 5 months (0.42 years or 5.05 months), from winter to early summer.

The M_2 specimens from Turó de la Rovira display an x_0/X ratio ranging from 0.27 to 0.59, showing a lambing period of three and a half months (0.32 years or 3.5 months) from spring to summer.

Oxygen sequences obtained in the M_3 could be all modelled except for the teeth MC M3 20160 and TR M3 831, which provided short sequences and not enough sinusoidal variation in oxygen values. In Mas Castellar de Pontós, the normalised M_3 results (x_0/X_{real}) show individuals that fit well with winter-spring and late summer-autumn periods. At Tossal de Baltarga, the two M_3 specimens record a lambing season occurring exclusively between winter and spring. In Sant Esteve d'Olius, the three M_3 analysed show births occurring during summer and autumn. Finally, the M_3 results from Turó de la Rovira show births occurring during both winter-spring and late summer-autumn periods.

Discussion

Use of M_2 and M_3 at the time of inferring the duration and distribution of seasonal sheep births

Following the recent publication of a new modern reference set by Balasse and colleagues (2023), this study can combine, for the first time, data from second and third molars with a solid basis for interpretation. Results from all M_2s and M_3s analysed show that sheep lambing generally occurred all year round in the sites studied (Fig. 3). Beyond these general results, the precisely obtained data from the M_3s show some divergences from their respective M_2s, suggesting that the timing of crown formation in M_3 and its inter-individual variability between sampled specimens, may have affected our final interpretations. This observation has already been noticed in both modern (Blaise and Balasse 2011) and archaeological (Tornero et al. 2013) specimens,

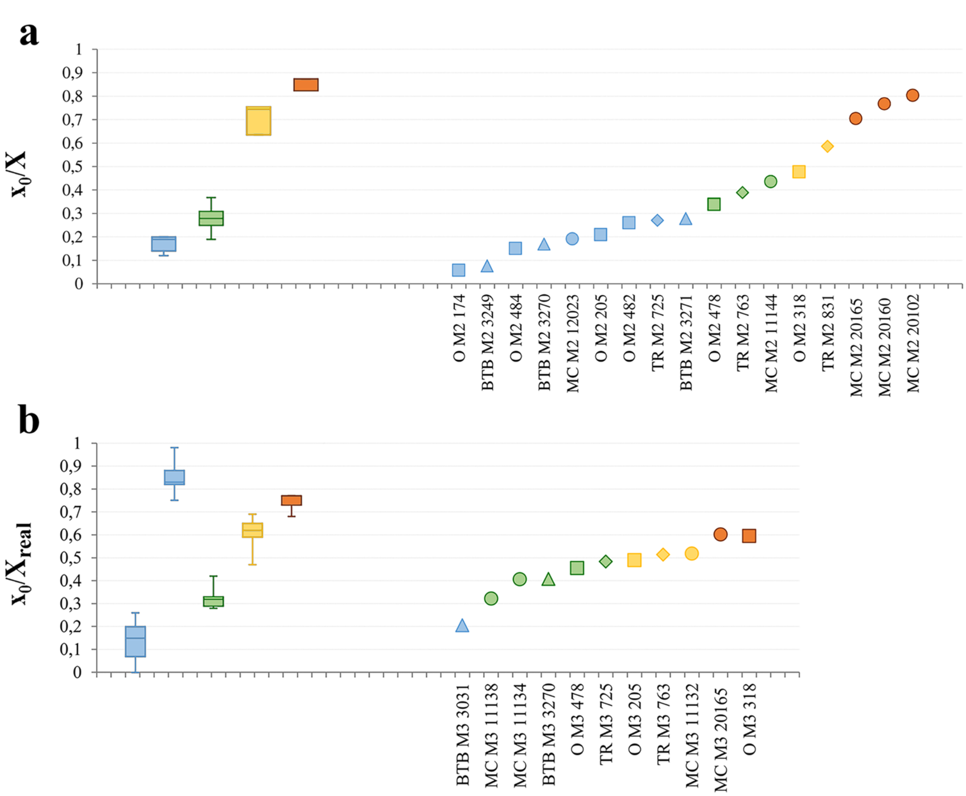

Fig. 3 **a** Results of the position in M_2 crown where the highest $\delta^{18}O_{V\text{-}PDB}$ values are obtained from the modelled datasets, normalised to the period (x_0/X). **b** Results of the position in M_3 crown where the highest $\delta.^{18}O_{V\text{-}PDB}$ values are obtained from the modelled datasets, normalised to the period (x_0/X_{real}). Mas Castellar de Pontós (MC, dots), Tossal de Baltarga (BTB, trinagles), Sant Esteve d'Olius (O, squares) and Turó de la Rovira (TR, rhombuses). On the left, season of birth results from modern reference populations: winter (blue), spring (green), summer (yellow), autumn (orange)

affecting this type of approach. Indeed, the results of the M_3s modelling show a lower seasonal resolution, which results in a higher x_0/X ratio than the birth interval resulting from the respective M_2s and a narrower birth period. According to Knockaert (2017) and Balasse et al. (2023), it is highly unlikely that inter-individual variability will result in incorrectly attributing a winter/spring birth to an autumn birth and vice versa. As a consequence, spring births should be clearly distinguishable from autumn ones. In our study, data from the archaeological M_3s show a bi-modal distinction between natural birth (winter/early spring) and out-of-season (late summer/autumn birth), which agrees with the data provided by the M_2s.

This study includes nine pairs of M_2s and M_3s from the same individuals; for seven of them, both M_2 and M_3 could be modelled. All modelled pairs exhibit an average difference of 0.17 (2.02 months) between the results of M_2 (x_0/X) and M_3 (x_0/X_{real}); nevertheless, all pairs of M_3 are in the same seasonal group as their corresponding M_2, corroborating what Knockaert and Balasse and colleagues stated. In the case of the two unmodelled M_3s (MC M3 20160 and TR M3 831), the oscillation of their sequence suggests, according to the reference by Balasse et al. (2023), that they belong to the summer/autumn group, the same as their respective M_2s. Therefore, inter-individual variability in the timing of the third molar growth can generate different levels of inaccuracy; however, these do not result in a misattribution of the birth group. At the time of the interpretation of the archaeological results, the best scenario remains to rely on both M_2 and M_3. Indeed, the archaeological M_3 display almost the same imprecision shown by modern references. Based on Balasse and colleagues (2023), the inter-individual variability in the M_3 timing of development of modern Lacaune ewes is approximately 1.5 months, whereas modelled and normalised M_2 and M_3 data obtained from individuals of the early 5th millennium cal BC from Cheia (Romania), show a higher variability, but still less than 2 months (1.8 months) (Tornero et al. 2013; Knockaert 2017). Thus, inter-individual variability bias was apparently present and similar in Iron Age Iberian sheep; moreover, it appears that this was slightly higher than observed in modern and early Eneolithic sheep in Europe.

Due to this methodological constraint, to infer and discuss the timing, duration and distribution of seasonal livestock births, we have chosen to focus on data obtained exclusively from M_2s.

Season and seasonality of sheep birth

Under temperate climate, sheep lambing season naturally occurs from late winter throughout spring (Hafez 1952; Jewell and Grubb 1974; Santiago-Moreno et al. 2000; Gootwine 2011; Gómez-Brunet et al. 2012). Indeed, in the absence of anthropogenic intervention, this represents the most common pattern in present-day and prehistoric husbandries in temperate Europe (Balasse et al. 2023). Therefore, the significant presence of autumn births necessarily indicates an extension of the natural breeding season and, as a result, a wider fertility period. Nowadays, autumn births are a common occurrence and a feature of farming systems in the Western Mediterranean region. As previously mentioned, the earliest evidence of this practice in this area dates back to the Early Neolithic and has been found at Taï and Gazel (Tornero et al. 2020). Furthermore, the Early Neolithic site of Chaves (Sierra et al. 2021), the Middle and Late Neolithic phases of Els Trocs (Tejedor-Rodríguez et al. 2021), the Middle Neolithic site of Auriac (Fabre et al. 2021) and Llo during the Middle/Late Bronze Age (Knockeart 2017) are additional isolated cases of site reporting autumnal lambing. Therefore, the interest does not lie in finding evidence of the presence of de-seasonalisation, but rather in verifying its spread and whether it is used systematically or not in the Iron Age and if this was linked to particular socioeconomic circumstances. Given the assumption, the results presented here provide a first evidence of livestock reproductive strategies during the Middle/Late Iron Age period in the Western Mediterranean region.

The seasonal distribution of births at the four archaeological sites is shown in Fig. 4 through a circular graph reflecting a complete annual cycle (Balasse et al. 2020). According to the data, in the north-eastern peninsula dating back to the Mid- and Late Iron Age, sheep births occurred all year round, but with substantial differences in each settlement.

A seasonal bi-modulated reproductive pattern was observed at Mas Castellar de Pontós, where lambing occurred during two different birth seasons: from late winter to late spring and in autumn. Furthermore, autumn births took place in a limited period (just over a month), suggesting the results of synchronised strategy by herders. Here, both "out-of-season" births and their synchronisation are interpreted as the results of herders' manipulation and deliberate strategic choices. Autumnal lambing, resulting from spring mating, implies a deep understanding and extensive knowledge of sheep reproductive physiology by herders; furthermore, specific attention and management of the livestock are essential. Control of female–male interactions is required, separating rams from ewes and bringing them together at a predetermined time, i.e. at the end of the fertility period (Tornero et al. 2020; Balasse et al. 2023). The availability of abundant forage resources during autumn/winter lactation represents an additional prerequisite for "out-of-season" births (Tornero et al. 2020; Balasse et al. 2023).

Tossal the Baltarga provides an entirely different seasonal reproductive pattern. Here, births occurred over a

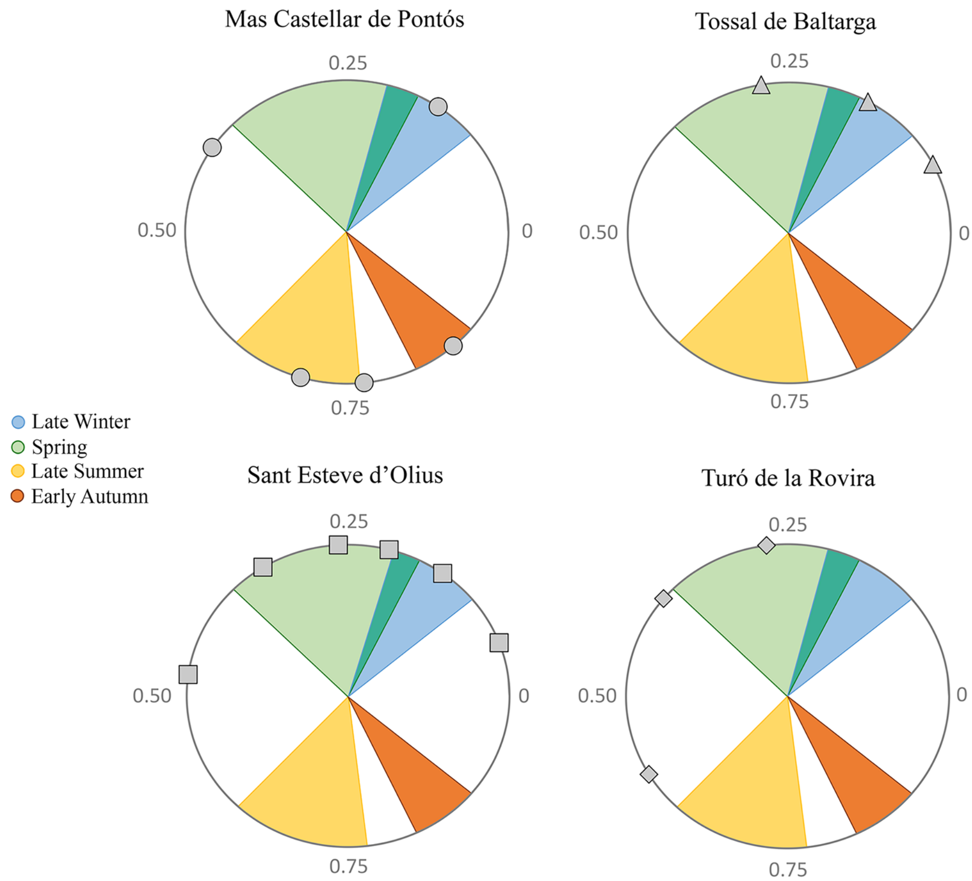

Fig. 4 Distribution of sheep births in the four study sites, as reflected by the position of the maximum $\delta^{18}O_{V\text{-}PDB}$ value in M_2 crown (x_0/X). The birth season is compared with modern reference populations with a known date of birth and potential agreement with successive calendar months (Blaise & Balasse 2011, Balasse et al. 2012, Balasse et al. 2017, Tornero et al. 2018 and Balasse et al. 2020). Archaeological sheep are represented in grey shapes, whilst the modern ones, counterclockwise, by blue, green, yellow and orange colour areas

relatively restricted time frame (2.5 months), from late winter to mid-spring, in agreement with the natural sheep lambing season. Therefore, no modifications aimed to extend or shift the expected breeding season due to anthropogenic intervention have been detected. On the other side, a herders' strategy may have resulted in births concentrated in 2.5 months.

The remaining two settlements, Sant Esteve d'Olius and Turó de la Rovira, are characterised by a third, distinct type of reproductive pattern. Due to the herders' interference in sheep reproduction, both settlements exhibit a prolonged lambing period. At Sant Esteve d'Olius, births occurred throughout 5 months, from winter to early summer, with a significantly extended lambing period compared to the natural breeding season. The same pattern is observed at Turó de la Rovira with a 3.5-month-long birth period. Although it is more restricted than Sant Esteve d'Olius', the lambing period is still longer than the natural one and is, therefore, the product of anthropogenic scheduling.

Livestock management and exploitation

Taking into account the data presented and discussed before, we propose that the different strategies deployed in the four sites are direct consequences of choices dictated by the economy and social organisation of each settlement, and also by the environmental conditions surrounding them. Indeed, results show a great variety in husbandry management and goals.

The most complex herding system is observed at Mas Castellar de Pontós, where the presence of two different birth seasons suggests a division of the herd into two groups of females giving birth at different times of the year. Herders probably regulated "out-of-season" lambing as part of a husbandry strategy aimed at the intensive exploitation of year-round secondary products (Gómez Brunet et al. 2012; Messana et al. in press). The results of zooarchaeological studies conducted on the faunal remains provide additional support for this hypothesis (Colominas 2008b, 2013a): indeed, the data suggest that, according to a predominance of adult and old individuals (from 48 to more than 96 months old) and mostly females, caprine livestock was primarily exploited to obtain secondary products, i.e. milk and wool. Furthermore, the increase in herd size may have been a further reason for requiring two different reproductive seasons. On this subject, according to Colominas (2013a), the rural establishment would have counted on a flock of approximately 60–80 individuals. Thus, the constant availability of a consistent number of individuals to be either sacrificed or exploited during their lifetime or to be exchanged as trade products would have been ensured. Finally, birth synchronisation by herders enabled them to focus all of their efforts on monitoring lambing and taking care of the youngest animals at a given time (Balasse et al. 2020). This complex herding system also implies that, at Mas Castellar de Pontós, herders had to provide the adequate amount of pasture resources required to support autumn and winter lactation. During the Iberian-Roman period, warmer and/or moister conditions and a strong seasonality with frequent precipitations in the cold season characterised the whole Mediterranean basin, particularly in the north-western Mediterranean (González-Sampériz et al. 2017). Consequently, at Mas Castellar de Pontós, herders could offer a sufficient quantity of forage to sustain autumn and winter lactation, relying on favourable climatic conditions. Furthermore, the integration of fodder from cereal cultivation might be used to feed the herd. The presence of both winter and spring crops at the site would have allowed the availability of crop residues for a large period of time during the year, particularly during those seasonal times when pasture resources are at their lowest.

The environmental conditions and the economic necessities in Tossal de Baltarga were totally different. The high mountain settlement is located in a constrained environment, where the vegetation is completely covered by snow during winter. At the same time, the site was a control point of mountain routes. Therefore, the reproduction pattern documented here was in accordance with the livestock necessities of their inhabitants. The best strategy was hence to rely on natural births in late winter/spring, with a reduced duration to minimise the labour of caring for pregnant and newborns and to ensure their survival. It was not convenient for the Tossal de Baltarga inhabitants to have a prolonged lambing season or even less autumn births. The latter, indeed, would have forced newborns to face the harsh winter in the Pyrenees during their first months of life. On the other hand, late winter/spring births allowed the newborns to approach the cold winter temperatures with the right physical condition to get through it. Zooarchaeological studies show the presence of sheep from different ages at the site, from 2 to 6 months old to 4 years old, with a slight predominance of adult individuals (24–48 months old) and an absence of old individuals (more than 72 months old). These data suggest the preferential use of sheep as meat producers. Neither any bone belonging to perinatal, neonatal or infant individuals has been recovered that could correspond to deaths related to environmental conditions.

The data from Sant Esteve d'Olius and Turó de la Rovira, located in an inland region and on the coast respectively and with different specific functions (see 2. Sites), are more difficult to interpret. The isotopic data shows the presence of a single group of births, but with a longer lambing period than the natural one. Is this choice the result of the demand for secondary products for a longer period of time, but not throughout the whole year? Or are we seeing a concrete moment within a breeding management system that is setting the stage for a "de-seasoning" of the herd in autumn? According to zooarchaeological data, sheep were mainly exploited in both settlements to obtain meat and, secondarily, wool and milk (Colominas 2013b, 2019). Therefore, secondary products had a significant economic role in both sites, but not as much as seen at Mas Castellar de Pontós. This may explain the requirement for a longer lambing period without the seasonal separation into two distinct groups. However, it is difficult to determine whether these prolonged lambings were planned within the agro-pastoral calendar or resulted from a "catch-up mating" setup due to low spring fertility (Balasse et al. 2023).

Conclusion

An insight into different sheep seasonal reproductive patterns adopted by the Middle/Late Iron Age societies in the north-eastern Iberian Peninsula is provided in this paper. Based on the results, a first and innovative glimpse into a complex and specialised livestock husbandry during the third century BC can be gained. Sequential oxygen isotope analyses in the second and third lower molars of sheep from four different sites reveal that sheep were generally able to give birth all year round. De-seasoning of the flock, however, was not practised systematically in every settlement; planning and management of sheep births were determined by economic purposes and environmental forces. As a result, the four sites studied here display different husbandry models: the demand for year-round availability of secondary products forced the co-presence of two different lambing periods at Mas Castellar de Pontós; at Tossal de Baltarga, the duration and the period of births was according to the economic necessities, and it also had to adapt to environmental restrictions; the cases of Sant Esteve d'Olius and Turó de la Rovira represent an in-between compared to the two previous models, with the possibility of manipulating the flock in both duration and period of births, but with no autumn lambing needed.

It is evident that, during the Iron Age, Iberian herders possessed excellent knowledge about sheep reproductive physiology and knew how to apply it according to the desired and sustainable type of exploitation. In order to be able to breed sheep at different times of the year, it was necessary to have a number of people dedicated exclusively and specifically to planning the management and exploitation of the herds, starting from the control of the reproductive calendar. This huge technical effort inevitably suggests that husbandry played a significant role in the economy of these communities and was perfectly fitted into the agricultural schedule. Indeed, it must be kept in mind that agriculture, and specifically cereal production, has always been considered the main activity, thanks, fundamentally, to the archaeological evidence of silo fields. This study highlights how, during the third century BC, a considerable workforce, technical knowledge, time and resources were employed in livestock practices. The data provides evidence that sheep births were intentionally manipulated by herders in two distinct ways: on the season and on the duration of the lambing period. Therefore, oxygen isotope data combined with zooarchaeological information has allowed us to propose that animal husbandry also contributed significantly to the economy of these communities. It has also allowed documenting how communities controlled sheep reproduction in relation to the products they wanted to exploit. On the other hand, isotope analyses have demonstrated that distinct livestock breeding strategies were adopted by different communities in relation to their own environmental conditions, economic needs and political decisions. Extending the research to additional Iron Age Iberian settlements is required in order to address the new questions and insights that have emerged from the data gathered. Indeed, the study of several settlements with different functionalities and localised in different environments is necessary in order to define the husbandry practices, with all their nuances, that characterised Iberian societies and to search for possible economic, political and/or environmental patterns. This will allow us to know whether these different reproductive patterns and livestock management practices were part of one integrated system or reflect multiple and separated groups of herders. Finally, the results presented in this paper need to be complemented by further ongoing isotopic studies related to livestock diet and mobility; the huge amount of data obtained will allow a further and innovative immersion in the management and exploitation of sheep livestock by the Iberians. Therefore, it is clear that the potential of data acquired through the implementation of biogeochemical analyses in order to provide knowledge about protohistoric societies is enormous, and it is imperative to exploit it.

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Code availability Not applicable.

Declarations

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Conflict of interest The authors declare no competing interest.

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