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# Milk and meat exploitation, autumn lambing and use of forest resources in Neolithic Corsican sheep farming systems (fifth to third millennia cal BC)

Mélanie Fabre<sup>a,\*</sup>, Vianney Forest<sup>b,c</sup>, Christophe Ranché<sup>b,c</sup>, Denis Fiorillo<sup>a</sup>, François Casabianca<sup>d</sup>, Jean-Denis Vigne<sup>a</sup>, Marie Balasse<sup>a</sup>

<sup>a</sup> AASPE « Archéozoologie, archéobotanique: sociétés, pratiques, environnements », CNRS, MNHN, Paris, France

<sup>b</sup> INRAP Institut National de Recherche Archéologique Préventive, Midi-Méditerranée, France

<sup>c</sup> TRACES Travaux et Recherches Archéologiques sur les Cultures, les Espaces et les Sociétés, UMR 5608 CNRS-Université Toulouse Jean Jaurès, France

<sup>d</sup> LRDE Laboratoire de recherche sur le développement de l'élevage, INRAE Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement

**Keywords:** Neolithic, Sheep farming, Corsica, Stable carbon isotopes, Stable oxygen isotopes, Mortality profiles, Modern reference set

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## ABSTRACT

*Corsica has been inhabited since the ninth millennium BC, but it is only from the sixth millennium BC onwards, that Neolithic societies originating from Italy settled mostly along coastal areas but also inland, in high mountainous areas. By then, Corsica was already experiencing some Mediterranean climate trends and was covered with dense forests. In order to assess how these Neolithic societies sustainably occupied this new insular territory, we need to understand how the local environment and resources were incorporated in the pastoral system. Osteological and isotopic analyses on remains from the sites of Araguina Sennola (late fifth – early third millennia cal BC) and Montlaur (4100–3600 cal BC) investigated the key parameters of these husbandry systems. Sheep mortality profiles from dental remains suggest mixed meat and milk exploitation. Modelled intra-tooth variations of oxygen isotope ratios ( $\delta^{18}O$ ) revealed extended birth season, including autumnal lambing. Carbon isotope ratios ( $\delta^{13}C$ ) showed high seasonal variation, involving forest resources in winter, as well as high- $\delta^{13}C$  summer plant resources, possibly C4 plants from coastal salt marshes. This raises the question of the seasonal mobility of herds. Great inter-individual variability in  $\delta^{13}C$  values reflects variable degrees and patterns of mobility, suggesting that herders adapted to the conditions of the contrasted Mediterranean landscape.*

## 1. Introduction

The earliest undisputable evidence of human presence on the Corsico-Sardinian island massif dates to the Mesolithic period, to the ninth millennium cal BC (Costa et al., 2003, Perrin et al., 2022). In the course of the sixth millennium cal BC, Neolithic societies originating from Italy mainly dispersed along coastal plains (Lugliè, 2018; Perrin et al., 2022), but also ventured further inland, as indicated by traces of Early Neolithic presence at Grotta Southwell, Vivario (Perrin, 2015), and even up to the high mountains, as evidenced by the occupation at the Castelli Shelter, Corte (Mazet et al., 2014). At that time, the land-based mammalian fauna was only composed of four small endemic species (Vigne, 1992), left over from the Late Glacial autochthonous stock: a small lagomorph (*Prolagus sardus*), and three large-sized small mammals, a vole (*Tyrrhenicola henseli*), a field mouse (*Rhagamys orthodon*) and a shrew (*Episorriculus sp.*). The Neolithic diffusion in Corsica triggered the renewal of mammalian fauna on the island, with the introduction of

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\*Corresponding author.

E-mail addresses: melanie.emilia.fabre@gmail.com (M. Fabre), vianney.forest@inrap.fr (V. Forest), christophe.ranche@inrap.fr (C. Ranché), denis.fiorillo@mnhn.fr (D. Fiorillo), fcasacorte@gmail.com (F. Casabianca), jean-denis.vigne@mnhn.fr (J.-D. Vigne), marie.balasse@mnhn.fr (M. Balasse).

domestic and synanthropic species now composing the mammalian diversity of Corsica (Vigne, 1988, 1999). Domestic sheep (*Ovis aries*), goats (*Capra hircus*) and pigs (*Sus scrofa*) were introduced during the sixth millennium cal BC, together with the fox (*Vulpes vulpes*), followed by cattle (*Bos taurus*) and dogs (*Canis familiaris*), possibly a little later (Vigne, 1984, 1987, 1988, 1992, 1999). The earliest evidence of agriculture in the pollen record is found in South Corsica at 5350 cal BC (Revelles et al., 2019).

During the Early Neolithic (sixth and early fifth millennia cal BC), the animal-based subsistence economy relied on hunting and fishing at possibly temporary sites (Araguina-Sennola, Bonifacio, South Corsica), but was also mostly based on caprine and pig breeding at other sites located in the coastal plain (Basi, Serra-di-Ferro, South Corsica; Vigne, 1988). During the fifth millennium BC (Middle Neolithic), sheep breeding played an important role in the economy. It was mainly oriented towards dairy farming, but also meat production to a lesser extent, and possibly hair exploitation (Vigne, 1988). However, it is difficult to grasp the mechanisms of this evolution due to the scarcity of sites (Vigne, 1985). Our research aims to further our understanding of how these Neolithic pastoral societies exploited highly contrasted environments, stretching from the coastal plains to the high mountain massifs of Corsica (maximum altitude of 2700 m), with a focus on southern Corsica.

In this study, the analysis of mortality profiles was used to approach flock demography management linked to production aims, but also to provide elements concerning the temporality of site occupation. Sequential stable isotope analyses of tooth enamel were conducted to investigate the seasonal pace of these husbandries. Autumnal lambing is typical of present-day Corsican caprine farming, in contrast to winter/spring lambing at higher latitudes in Europe. Spring lambing was also the dominant pattern in Europe from the sixth to the third millennia cal BC (Balasse et al., 2020), while autumn lambing has been identified at Early and Middle Neolithic sites in southern France (Tornerio et al., 2020; Fabre et al., 2021). The hypothesis of autumnal lambing in the Neolithic period in Corsica was tested using stable oxygen isotope ratios. Through the concomitant analysis of stable carbon isotope ratios, we investigated how sheep were herded between open pastures and forested areas on a seasonal scale. Forest pasturing as well as tree leaf foddering are attested in the Mediterranean area (Tornerio et al., 2020), providing additional forage resources when open pastures are scorched by summer drought (Thiébaud, 2005), or covered with snow at higher elevations in winter (Halstead, 1998). This study offers a first overview of the routes and temporal organization of these Neolithic herding systems. However, the topic is vast and much remains to be described.

## 2. Environmental and zootechnical contexts

Pollen analyses showed that *Erica arborea* forest (white heather) dominated the western side of the island at low and medium elevations (0 to about 1500 m) during the Atlantic period (7000–4000 cal BC), spanning the Early and Middle Neolithic in Corsica, mixed with *Pinus laricio* at higher altitudes (up to 1800 m). On the eastern side of Corsica, low-altitude plains (0–100 m) were colonized by deciduous oak forests, mixed with *Erica arborea* forest at higher altitudes from 100 m to 1500 m, while *Pinus laricio* (Corsican black pine) was predominant at higher elevations. The following Sub-boreal period was marked by the expansion of the evergreen oak (*Quercus ilex*) on the northern coast, in the high mountains of the center and north and on the eastern plain, from 4500 cal BC onwards (Reille 1992). Present-day *E. arborea* matorral in Corsica does not exceed 2–3 m in height, but *Erica* forests little impacted by human activities can reach much greater heights (up to 20 m; Poher et al., 2017). The environment in Neolithic Corsica must therefore have been predominantly closed.

The history of vegetation and coastal wetland conditions in southern Corsica is documented by recent interdisciplinary paleoenvironmental studies (Poher et al., 2017; Revelles et al., 2019). The predominance of *Erica* is confirmed for the Early Neolithic, consisting most probably of *Erica* trees. However, this forest was soon impacted by human activities after 5300 cal BC, and probably took the form of a pasture-woodland landscape, i.e., low scrubland and pasture components in heath-dominated vegetation. *Quercus ilex* expanded later in southern Corsican coastal sites than further north (ca. 3500 cal BC in Cavallo, Poher et al., 2017; or 2500 cal BC at Piantarella, Revelles et al., 2019) and evergreen forests were rather insignificant. In the earliest Neolithic, freshwater conditions in coastal wetlands could have favoured agriculture. During the Early Neolithic (from 5400 cal BC), a rising sea level led to the development of salt marshes. Later, during the Middle and Late Neolithic, freshwater conditions prevailed again after the development of coastal barriers. However, during that time, the persistence of *Chenopodiaceae*, including salt-tolerant plant species, suggests that salt marshes occurred locally (Revelles et al., 2019). Corsica therefore displayed different kinds of pasture areas (matorral and forests at low to mid-altitudes and open grasslands at higher

altitudes) with a diversity of fodder resources, and different climates (dry and warm at low altitudes, cold and humid at higher latitudes). Not all of these pasturelands were hospitable all year round but potentially complemented each other throughout the seasons.

Moreover, some elements of the Mediterranean climate as it is defined today may already have existed in the north-western Mediterranean at that time (Peyron et al., 2010; Magny et al., 2012, 2013; Sabatier et al., 2017; Azuera et al., 2020). Corsica could therefore already have been experiencing dry summers, which constitute a major constraint for grazing, due to insufficient grass resources during a possible lactation season. On the other hand, rainy autumns and cool winters would have favoured the revival of vegetation. Modern sheep husbandries in the western Mediterranean take advantage of this seasonal pattern to schedule autumn lambing (Todaro et al., 2015), in contrast to predominant spring lambing elsewhere in temperate Europe (Hafez, 1952). Indeed, autumnal lambing prevails today in Corsica (Lacombe et al., 2016). This system became predominant at the end of the nineteenth century when the capacity of Corsican sheep breeds for out-of-season breeding was exploited to enhance cheese production in winter and meet the needs of the dairy industry (Lacombe et al., 2016; Lacombe, 2018). Before this relatively recent change, sheep lambed in winter and farmers processed milk into cheese while they were on summer pastures in the mountains (Ravis-Giordani, 1983, Delfosse and Prost, 1998). Herders thus demonstrated the capacity of their dairy breeds to adapt to new production systems according to economic and social conditions. Some breeders are currently returning to a pre-industrial model in order to add value to their cheese by catering for the needs of summer tourists (Lacombe et al. (2016). These technical systems are therefore not immutable in space or in time, but are dependent on production aims, the availability of fodder resources and cultural choices (Delfosse and Prost, 1998). Nevertheless, we cannot rule out the possibility that autumn lambing husbandry systems may have existed in more ancient times.

### 3. The Neolithic sites of Araguina-Sennola and Montlaur (Bonifacio, Southern Corsica, France)

This study describes sheep farming systems at two Neolithic sites: Araguina-Sennola (late sixth-early third millennia BC) and Caserne de Montlaur (early fourth millennium BC). These two sites are located in the very southern tip of the island, close to Sardinia, and open onto the sea (Fig. 1). They may thus have played an important role in cultural and commercial exchanges between the two islands, and may even have been part of a larger exchange network in the Tyrrhenian Sea (Perrin et al., 2022). Araguina-Sennola also holds a strategic position between coastal and inland areas and might have been a stopover place on seasonal herd mobility routes. Most Corsican soils lie on acidic effusive or crystallophyllian substrata, which are not conducive to bone preservation. However, these two sites are located on the limestone plateau of Bonifacio, which is more favourable to bone preservation. They both yielded faunal assemblages with large dental series, and are well suited to the investigation of sheep exploitation strategies. Montlaur is an unpublished series, while the Araguina faunal assemblage constitutes a reference series for the Neolithic of Corsica and more generally, for the Tyrrhenian islands (Vigne, 1999).

The vast Araguina-Sennola rock shelter is one of the oldest known sites in Corsica. It is located in a narrow valley on the northern edge of the Bonifacio ria, on one of the main circulation routes between the ria and the Bonifacian limestone plateau. It seems to be a temporary coastal habitat. Radiocarbon dates indicate that it was settled throughout the Holocene, from the Mesolithic to the Middle Ages (Gagnère et al., 1969; Lanfranchi et al., 1972; Lanfranchi and Weiss, 1977). The Neolithic stratigraphic succession was divided into four phases (Lanfranchi and Weiss, 1977):

ARA 1: Early Neolithic (layer XVII) late sixth – early fifth millennia cal BC.

ARA 2: Middle Neolithic (layers XVI-XIV) late fifth and early fourth millennia cal BC.

ARA 3: Late Neolithic (layers XIII-XI) second half of the fourth millennium cal BC.

ARA 4: Final Neolithic (layers XI-X and VI J) third millennium cal BC.

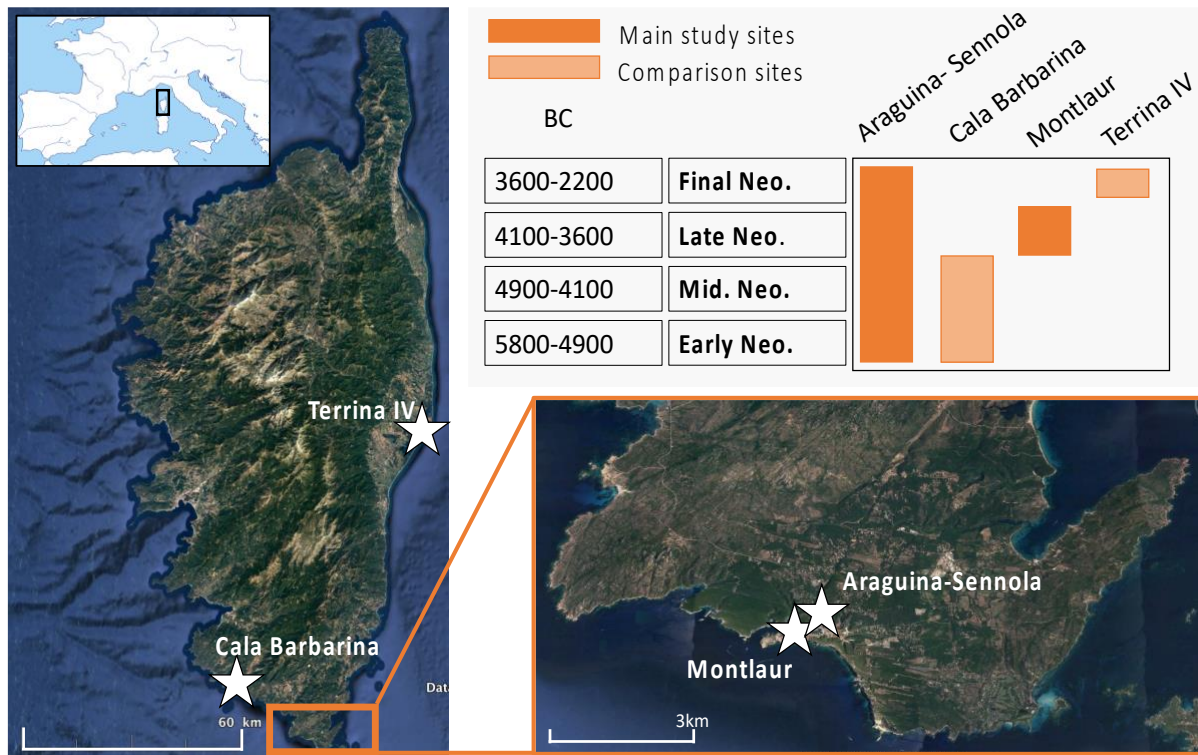


Fig. 1. Location and chronology of the two studied sites (Montlaur and Araguina-Sennola) and two other Neolithic sites used for comparison (Terrina IV and Cala Barbarina). Map from Google earth Pro.

The abundant and exhaustively studied vertebrate fauna (Vigne, 1984, 1987, 1988, 1999) from ARA 2–4 consists predominantly of *Prolagus sardus*, Caprinae, cattle and swine. The animal subsistence economy was preferentially based on husbandry, with varied contributions of small game, fish and shellfish (Vigne, 1988). A total of 8867 large mammal specimens are unevenly distributed between the different settlement phases, and 2651 (30%) of them have been identified (Vigne, 1988). Caprinae (sheep: *Ovis aries*, and goats: *Capra hircus*) total 1712 remains or 65% of the determined large mammals and sheep largely outnumber goats (88%; N = 174, Vigne, 1988), as in most Mediterranean Neolithic sites (Navarrete et al., 2019) (Fig. 2). If we consider the dietary contribution of each species estimated by the bone weight (%), references in Vigne, 1992), the animal economy mostly relied on *Prolagus* hunting during the Early Neolithic (ARA 1). This was replaced by husbandry during ARA 2–4, primarily by sheep breeding, with secondary cattle and swine breeding.

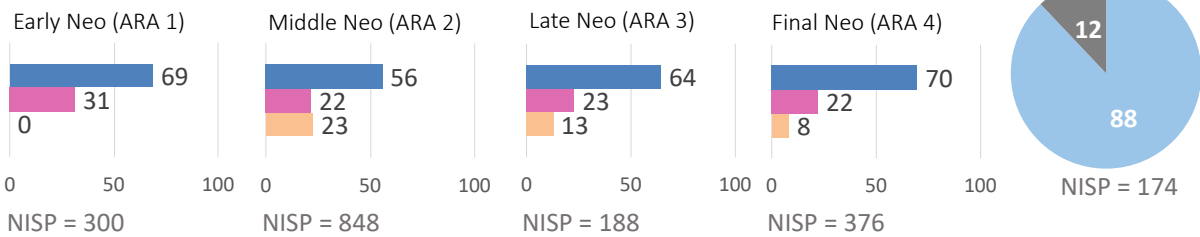
The archaeological site of Montlaur was discovered during a rescue excavation conducted by the Institut National de Recherches Archéologiques Préventives (Inrap) between 2014 and 2017, during the renovation of the military barracks. It is located in the ‘upper city’ of the Bonifacio peninsula. The Neolithic open-air settlement can be divided into two distinct loci. The first resembles a vast dumping ground, while the second is associated with a domestic activity area, although no dwellings have yet been found. Radiocarbon dating of bones by the Poznan laboratory suggests continuous occupation between 4045 and 3516 cal BC 1σ or 3991 and 3553 cal BC 2σ (Table 1), which relates to the extreme end of the Middle Neolithic and the Recent Neolithic (Tramoni and D’Anna, 2016). Only 6371 of the 37,952 faunal remains have been determined (17%) by two of us (M. F. & V. F.), due to a high fragmentation rate. The total number of sheep and goat remains is 2851, accounting for 45% of the large mammal spectrum, followed by cattle (33%) and swine (22%). Over a quarter of the caprine remains – 27% - are isolated teeth. Sheep are much more abundant than goats (92%; N = 585; Fig. 2). The animal economy at Montlaur mostly relied on livestock farming, with a main focus on sheep breeding when considering the number of remains (NR), followed by cattle and swine, even though cattle accounted for 70% of the meat intake, while sheep only accounted for 10%.

Context	Lab. code	BP	cal BC (1 $\sigma$ )	cal BC (2 $\sigma$ )
Bonifacio CM 1217	Poz-132920	5150 $\pm$ 35 BP	4045-3933	3991-3945
Bonifacio CM 1225	Poz-132919	5105 $\pm$ 35 BP	3883-3798	3873-3807
Bonifacio CM 1231	Poz-132921	5135 $\pm$ 35 BP	3994-3907	3983-3944
Bonifacio CM 1245	Poz-132922	4985 $\pm$ 35 BP	3806-3652	3795-3706
Bonifacio CM 1246	Poz-132924	4930 $\pm$ 35 BP	3779-3643	3711-3648
Bonifacio CM 2010	Poz-132953	5120 $\pm$ 35 BP	3881-3799	3865-3811
Bonifacio CM 2024	Poz-132954	4775 $\pm$ 30 BP	3640-3516	3589-3553

Table 1: Radiocarbon dating bones from Montlaur (Pozan laboratory) 1  $\sigma$  = 68.3%

#### Araguina Sennola: spectrum of large mammals fauna %NISP

Total NISP=1712



#### Montlaur: spectrum of large mammals fauna %NISP

Late Neolithic (4050-3600 BC)

NISP=6379

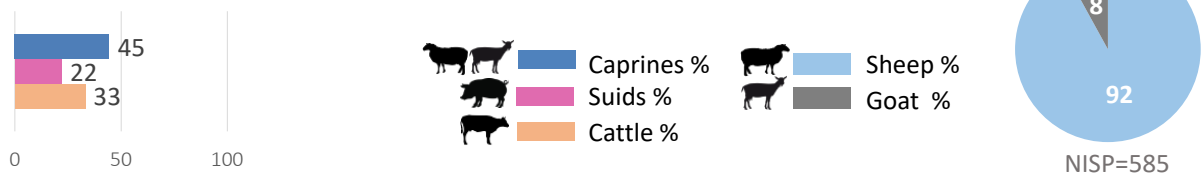


Fig. 2. Spectrum of large mammals at Montlaur and Araguina, and their percentage in the total number of remains (%NISP). Raw data for Montlaur from Borvon et al. (in progress), for Araguina from Vigne (1988).

## 4. Material

### 4.1. Material for osteological analyses

Our osteological analyses for Araguina-Sennola were based on the published dataset (Vigne, 1988), recently reviewed by the author himself. Mortality profiles are usually based on age data from lower dentition. At Araguina, the number of lower teeth was insufficient and we had to include upper teeth as well. A mortality profile was established for each horizon (N = 37, 30, 23, 19, respectively, for ARA 1 to ARA 4) (Supplementary material 1A).

Sample size at Montlaur was large enough to focus exclusively on lower teeth. As Montlaur presents many stratigraphic units (S.U.) deposited over a period of five centuries, we processed each assemblage separately (Supplementary material 1B). Three of them were well dated to around 3800 cal. BC: BCM1 (S.U. 1225, 1245, 1246; N = 96), BCM2 (S.U. 1231, 1217; N = 62) and BCM 3 (S.U. 2024, 2010; N = 22). We also selected two other assemblages with no radiocarbon dates in order to test the consistency of the results: BCM4 (S.U. 1202, n = 33) and BCM5 (S.U. 1219; N = 31). As they were statistically no different from each other, we combined all the assemblages in one dataset with a total of 244 teeth (Supplementary material 1C).

## 4.2. Archaeological material and modern reference series for stable isotope analyses

The distinction between sheep (*Ovis aries*) and goats (*Capra hircus*) was made on the basis of osteological criteria defined on lower teeth (Payne, 1985; Helmer, 2000; Halstead et al., 2002), the validity of which was statistically evaluated by Zeder and Pilaar (2010) and Gillis et al. (2011). Araguina-Sennola yielded few well-preserved second and third sheep molars. Three upper third molars ( $M^3$ ), two upper second molars ( $M^2$ ) and two lower second molars ( $M_2$ ) were sampled. The two  $M_2$  came from complete mandibles and could therefore be distinguished from the  $M_1$ . The sampled material contains one Early Neolithic molar, three Middle Neolithic molars and three other Final Neolithic molars. The teeth from Montlaur were mainly isolated as the mandibles were almost all splintered. The analysis of second molars was abandoned because the distinction between first and second molars is often uncertain in isolated teeth (Vigne 1988). We selected third molars with an early stage of wear in order to obtain sequences reflecting a complete annual cycle. In total, 21 lower third molars ( $M_3$ ) were attributed to sheep based on the criteria of Gillis et al. (2011), and were sampled at this site. Determining the birth season in Neolithic sheep involves comparisons with reference sets composed of modern sheep with known birth seasons (Balasse et al., 2012). The currently used reference sets comprise sheep from various breeds, including a Shetland cross (Balasse et al., 2012), a Ouessant  $\times$  Landes de Bretagne cross (Balasse et al., 2020), the Préalpes du Sud breed (Blaise and Balasse, 2011) and the Xisqueta breed (Tornero et al., 2018). In addition, five mandibles were collected from modern Corsican sheep. The selected ewes were between three and five years old. They were raised at mid-altitude in two farms located in the north of the island, oriented towards milk production with the main lambing season in autumn (Supplementary material 2A). The selected specimens were born in October. Depending on the wear stage of crowns, we analysed the  $M_2$ , the  $M_3$ , or both teeth. Five lower molars were sampled: COR Ovis 1 ( $M_2$  and  $M_3$ ); COR Ovis 2 ( $M_3$ ); COR Ovis 3 ( $M_2$ ); COR Ovis 4 ( $M_2$ ); COR Ovis 5 ( $M_2$ ) (Supplementary material 2A).

## 5. Methods

### 5.1. Demographic management and production orientation

#### 5.1.1. Mortality profiles

Sheep are overwhelmingly abundant in comparison to goats on the basis of long bones and the criteria ( $\geq 88\%$ ) in Boessneck et al. (1964), and so we did not make any distinctions on the strength of the tooth series. Demographic management is inferred from mortality profiles. Each remain was assigned to an age class based on Payne (1973) and Helmer (1995) for isolated molars. Absolute age estimates based on the observation of current benchmarks (Payne, 1973) are associated with these relative classifications. A histogram was generated from the observed raw frequency of teeth ( $N_i$ ) for each age class ( $i$ ). The reliability of the frequency of classes compared to each other was estimated through credibility intervals generated using the Dirichlet distribution as a prior distribution within a Bayesian framework (from 10,000 simulations). Statistical analysis was performed with the R software (R Core Team, 2019) from the script published by Gerbault et al., (2016). These intervals are associated with frequency density ( $y$ ) per unit of time ( $x$ ) for each of the classes and not with the frequency ( $xy$ ), i.e., the number of teeth for each age class ( $N_i$ ).

#### 5.1.2. Correspondence analyses

We implemented correspondence analysis (CA) to compare the Montlaur and Araguina-Sennola mortality profiles to two other Corsican Neolithic assemblages: Terrina IV (Aléria, third millennium cal BC – Vigne in Camps et al. 1988) and Cala Barbarina (Sartène, fifth-fourth millennia cal BC – Vigne, 1988) (Fig. 1). These two sites are the only existing regional datasets more or less contemporary with Montlaur and Araguina-Sennola. The two-dimensional kernel density estimates for age-at-death frequency distribution (i.e., one site) were obtained from the  $x$  and  $y$  coordinates generated by the CA for the 10,000 Dirichlet deviates of this site. This statistical analysis was performed using the script published by Gerbeault et al., (2016) with the R software (R Core Team, 2019).

## 5.2. Lambing season and food management

### 5.2.1. Principles of stable oxygen and carbon isotope analysis in enamel

Oxygen isotope ratios in bioapatite are mainly derived from oxygen isotopes in drinking water, which is itself related to local precipitation (Land et al., 1980; Longinelli, 1984; Luz et al., 1984; D'Angela and Longinelli, 1990). In temperate continental Europe, the  $\delta^{18}\text{O}$  of precipitation varies seasonally with ambient temperature, with the highest values in the warmest months, and the lowest in the coldest months (Rozanski et al., 1993). These seasonal variations are recorded in enamel during tooth formation and can be reconstructed by the sequential analysis of teeth. Individuals born in the same season record the same seasonal cycle sequence in a given tooth, and growth timing is fixed within species. Interindividual variability in the positioning of  $\delta^{18}\text{O}$  sequences in tooth is observed through the position of the maximum value of the  $\delta^{18}\text{O}$  cycle ( $\delta^{18}\text{O}_{\text{max}}$ ) (Balasse et al., 2003). By comparing the record of these cycles between different individuals, we estimate birth distribution, i.e., how births are spread out over the year (Bryant et al., 1996; Fricke and O'Neil, 1996; Balasse et al., 2003). Reference sets, composed of teeth from modern sheep with known birth seasons, are used for comparative purposes to determine the season of birth (Balasse et al., 2012).

The animal's diet on a seasonal scale is studied by the joint measurement of  $\delta^{18}\text{O}$  and stable carbon isotope ratios ( $\delta^{13}\text{C}$ ). Stable carbon isotope ratios in tooth enamel are related to the isotope composition of the plants making up the animal's diet. Intra-tooth variations in  $\delta^{13}\text{C}$  values provide information on changes in an individual's diet on a sub-annual scale. The landscape of Western Europe is predominated by  $\text{C}_3$  plants (Pyankov et al., 2010).  $\text{C}_4$  plants only represent a very small percentage in Corsica (1.55% of total flora), including 1.36% native plants (Collins and Jones, 1985), which could have been present in the Neolithic.  $\text{C}_4$  plants in Europe occur preferentially in maritime and ruderal habitats (Collins and Jones, 1985) and are expected in coastal saline environments. In open environments, present-day  $\text{C}_3$  plants have a mean  $\delta^{13}\text{C}$  value of  $-27\text{‰}$  (Kohn, 2010), which corresponds to  $-25.5\text{‰}$  for pre-industrial plants after correction for the fossil fuel effect ( $\approx 1.5\text{‰}$  Freyer and Belacy, 1983). In large herbivores, the isotopic enrichment factor between consumed plants and enamel bioapatite  $\delta^{13}\text{C}$  values is  $14.1\text{‰}$  (Cerling and Harris, 1999). Expected  $\delta^{13}\text{C}$  values in tooth enamel for animals feeding primarily on  $\text{C}_3$  plants grown in open environments are around  $-11.8\text{‰}$ . In arid environments (annual precipitation below 500 mm),  $\text{C}_3$  plants may have  $\delta^{13}\text{C}$  values higher than  $-25\text{‰}$  and up to  $-23\text{‰}$  (Kohn, 2010), or  $-21.5\text{‰}$  in pre-industrial times and  $-7.7\text{‰}$  in enamel. Above this threshold,  $\delta^{13}\text{C}$  values are related to  $\text{C}_4$  plants (or CAM plants or some lichens). In closed environments, the 'canopy effect' leads to lower  $\delta^{13}\text{C}$  values in plants due to restricted light (Van der Merwe and Medina, 1991; Bonafini et al., 2013). Values below  $-31.5\text{‰}$  refer to closed forests in present-day environments (Kohn, 2010), or  $-30\text{‰}$  in pre-industrial times, corresponding to  $-16.3\text{‰}$  in enamel for animals feeding exclusively in forested areas. The threshold below which  $\delta^{13}\text{C}$  values reflect a significant dietary contribution of forest resources is determined by reference to values measured in the collagen of Mesolithic aurochs from dense forest environments in Denmark ( $-22.4\text{‰}$  on average; Noe-Nygaard et al., 2005). Considering a  $5\text{‰}$  collagen-diet  $^{13}\text{C}$ -enrichment (Ambrose and Norr, 1993), and the  $14.1\text{‰}$  enamel-diet enrichment factor, the expected  $\delta^{13}\text{C}$  value in enamel is  $-13.7\text{‰}$ .

### 5.2.2. Sampling and isotopic analysis

Concretions and cementum were removed from the tooth surface by abrasion. Enamel was sampled on the buccal surface, on the medial lobe of the  $\text{M}_3$  and on the posterior lobe of the  $\text{M}_2$ ,  $\text{M}^2$  and  $\text{M}^3$ . Sampling is performed by drilling from the apex at regular intervals, perpendicularly to the tooth growth axis. Each sample is positioned on the crown by evaluating its distance from the enamel-root junction (ERJ). The collected enamel powder, weighing 2.5 to 20.1 mg, was pre-treated in acetic acid [ $\text{CH}_3\text{COOH}$ ] (0.1 M; 0.1 ml solution/mg sample; 4 h). Enamel powders from modern Corsican ewes were not pre-treated. Approximately 600  $\mu\text{g}$  of powder was then placed in an automated carbonate preparator (Kiel IV) coupled to an isotope mass spectrometer (Delta V Advantage). Stable carbon and oxygen isotope ratios were calibrated to VPDB using the international standard NBS 19. The accuracy and repeatability of the isotopic measurements are determined by the analysis of our in-house standard (Marbre LM normalized to NBS 19). Over the period of measurements, the concomitant analysis of 120 Marbre LM produced mean values of  $-2.07\text{‰} \pm 0.06 (1\sigma)\text{‰}$  for  $\delta^{18}\text{O}$  (expected value:  $-1.83\text{‰}$ ) and  $2.19\text{‰} \pm 0.03 (1\sigma)\text{‰}$  for  $\delta^{13}\text{C}$  (expected



value: 2.13 ‰). Analytical precision, determined by analysing 8 to 10 Marbre LM per analytical session, varied from 0.03 ‰ and 0.06 ‰ for  $\delta^{18}\text{O}$  and 0.02 ‰ to 0.05 ‰ for  $\delta^{13}\text{C}$  (Supplementary material 3).

### 5.2.3. Modelling

The position of  $\delta^{18}\text{O}_{\text{max}}$  in the tooth crown ( $x_0$ ) is determined after modelling the sequence according to an equation derived from a cosine function (Balasse et al., 2012). The modelling also determines the tooth crown distance over which the isotopic record covers an entire yearly cycle (the period;  $X$ ); this parameter is related to the size of the tooth. The period ( $X$ ) is used to normalize the position ( $x_0$ ) of  $\delta^{18}\text{O}_{\text{max}}$  on the tooth crown, to eliminate interindividual variability in tooth size. Interindividual variability in the ( $x_0/X$ ) ratio refers to birth distribution. The season of birth is then estimated by comparing the ( $x_0/X$ ) ratio with those measured in modern reference sheep teeth. We used pre-existing reference sets for the lower third molar (Balasse et al., 2023), the upper third molar (Balasse et al., 2020) and the second molar (Blaise and Balasse, 2011; Balasse et al., 2012; Tornero et al., 2018; Balasse et al., 2020). These reference sets were enlarged using the lower second and third molars from the Corsican modern sheep. The  $x_0/X$  ratios are reported on circular charts reflecting the cyclicity of seasonality (Balasse et al., 2020). Methodology for the construction of this chart may be found in Balasse et al. (2023).

The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sequences do not vary in phase (their maximum/ minimum values are not measured in the same location in tooth crown). The phase shift between the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sequences was modelled (Balasse et al., 2019) to observe how enamel  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values co-vary during the year. The  $\delta^{13}\text{C}$  values in  $\text{C}_3$  plants vary seasonally towards higher values in the summer, and lower values in the winter (Smedley et al., 1991). Consequently, in modern sheep feeding in the same pasture area throughout the year, the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sequences in tooth enamel vary almost in phase (phase shift 296-340°; Balasse et al., 2019). Deviations from this pattern may be interpreted as different food source contributions for part of the year due to foddering, or mobility between environments with different vegetation growth dynamics (Balasse et al., 2013; Knockaert et al., 2018).

## 6. Results

### 6.1. Mortality profiles

#### 6.1.1. Araguina-Sennola mortality profiles

The four mortality profiles of Araguina-Sennola correspond to the four stages of occupation of the site (Fig. 3 and Supplementary material 1A). All the different age classes present an overlap of credibility intervals. In the ARA 1 profile ( $N_i = 37$ ), classes A (0–2 months; Payne, 1973), B (2–6 months) and C (6–12 months), representing animals under one year of age, account for 46% of the  $N_i$ . They are over-represented in comparison with older animals; the frequency of class EF (2–4 years) is only 19%, while classes G (4–6 years) and HI (6–10 years and more) are not represented. Class D (1–2 years), which represents young adults, accounts for 38%. The ARA 2 ( $N_i = 30$ ) and ARA 3 ( $N_i = 23$ ) profiles do not statistically differ from each other (Fisher's exact  $p = 0.97$ ). The combination of these two profiles from the fourth millennium BC gives rise to ARA 5 ( $N_i = 53$  (Fig. 3 and Supplementary material 1A). In this profile, 33% of animals were slaughtered before the age of one year, 19% were young adults and 47% were adults (21% of which were over 4 years old: classes G and HI). ARA 4 ( $N_i = 19$ ) is not really representative due to small sample size. But we can point out the high representation (42%) of old sheep between 6 and 10 years or even older (class HI).

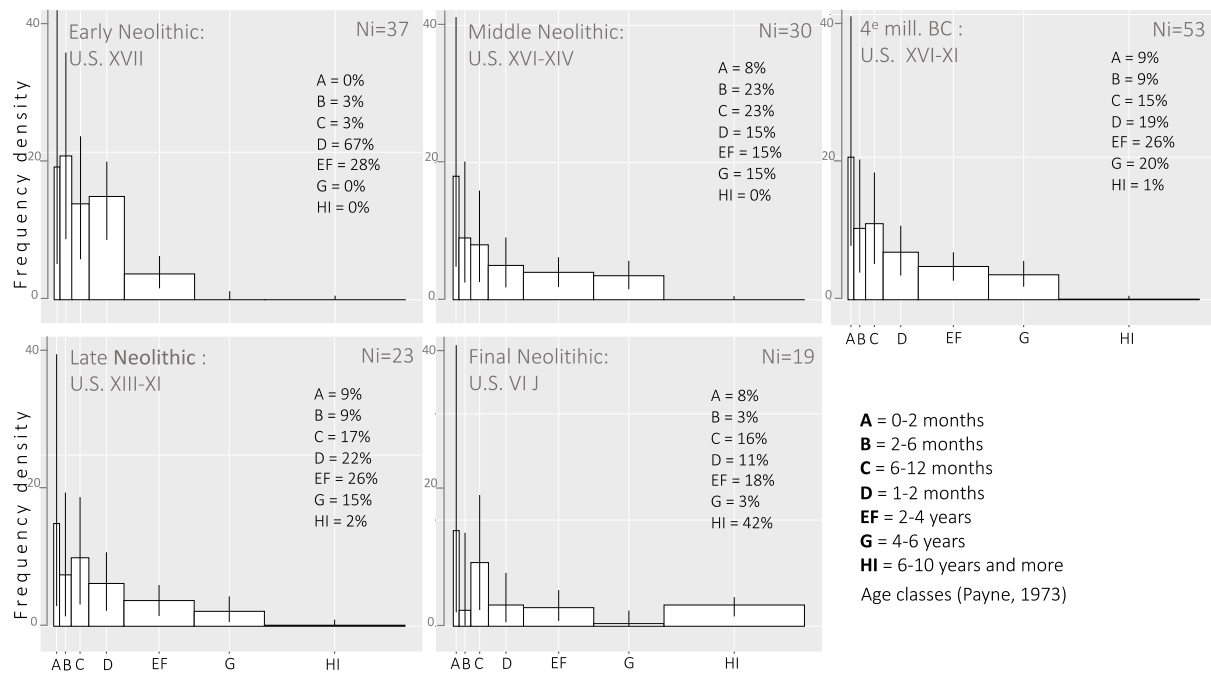


Fig. 3. Caprines mortality profiles at the Araguina-Sennola site as histograms based on the Number of teeth (Ni), associated with credibility intervals (Dirichlet distribution law; Gerbault et al. 2016). These are relative and not absolute age classes.

### 6.1.2. Montlaur mortality profiles

For the sheep mortality profile of Montlaur (Fig. 4), the five stratigraphic units were grouped together as no significant differences emerged between them (global Chi-square = 21.05, Freedom degree = 24,  $p = 0.64$ ; contributions and other tests in Supplementary material 1C). This profile comprises 244 remains, and can thus be considered as representative. Classes EF, then D and G, i.e., adult animals aged between 1 and 6 years, dominate the profile, accounting for 73% of the headcount. The presence of old animals is relatively significant (class HI = 9%). Young animals (under one year of age = classes A B and C) represent 18% with a low representativity of lambs less than six months old (classes A and B = 5%). There is however an overlap of credibility intervals within each pair of two consecutive age classes (A-B, B-C, C-D, etc.), except between EF and G, showing a real gap between these two classes. Otherwise, there is no mortality peak.

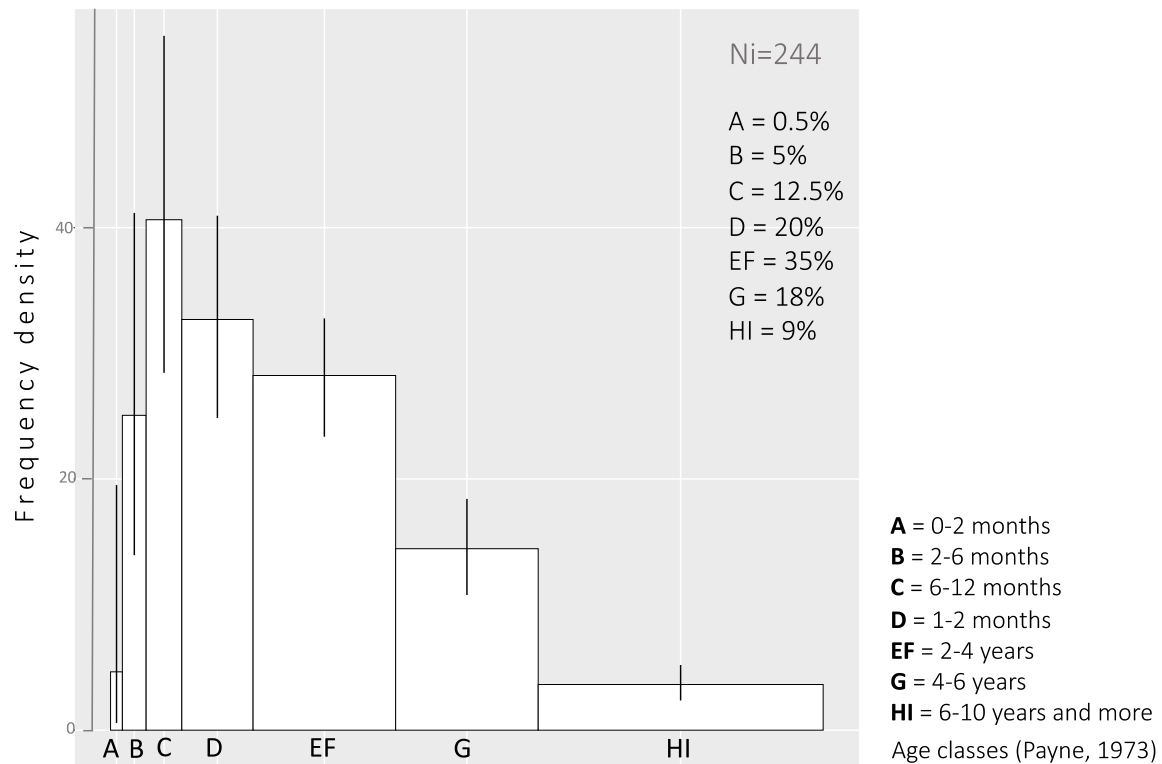


Fig. 4. Caprines mortality profiles at the Montlaur site as histograms based on the Number of teeth (Ni), associated with credibility intervals (Dirichlet distribution law; Gerbault et al. 2016). These are relative and not absolute age classes.

### 6.1.3. Correspondence analyses

CA displays a strong structure (significant global Chi-square), with the three first factors recruiting nearly 70% of the total inertia (Supplementary material 1D). Fig. 5 presents the F1xF2 projection of the Correspondence analysis of the Dirichlet simulations of the different mortality profiles from Montlaur and Araguina Sennola compared with the two reference Neolithic assemblages of Terrina IV and Cala Barbarina. Graphically, the different age classes are distributed on a parabolic profile (Guttman effect), revealing a gradient with the two extreme classes opposed to each other: A and HI (Fig. 5). The profiles cluster into three groups:

- Araguina-Sennola Early Neolithic with a strong A-B component corresponding to very young lambs (0–6 months).
- Terrina IV, Cala Barbarina and Montlaur are strongly correlated with intermediate age classes.
- Araguina Sennola Final Neolithic: with a strong HI component, i.e., very old animals (6–10 years).

Each of them indicates a different tendency in the slaughtering strategy. Altogether, they evidence chronological or site variations in husbandry strategies. Correspondence analysis and kernel density estimates of the four mortality distributions (Araguina-Sennola, Montlaur, Terrina IV and Cala Barbarina). Grey dots are some of the 10,000 deviates of the population frequency given the observed data, using the Jeffreys' prior, i.e. Dirichlet (0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5).

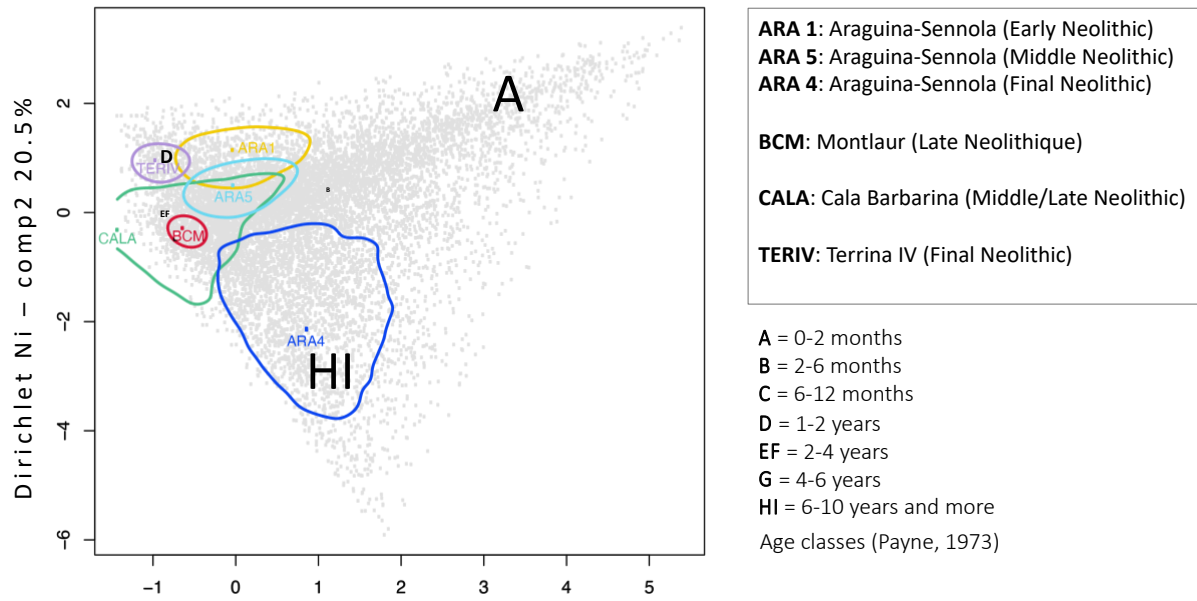


Fig. 5. F1xF2 projection of the Correspondence analysis of the Dirichlet simulations of the different mortality profiles from Montlaur and Araguina Sennola compared with the two other Neolithic assemblages of Terrina IV and Cala Barbarina.

## 6.2. Results from stable isotope analyses

### 6.2.1. Modern Corsican sheep

The results from modern Corsican sheep are presented in Fig. 6.  $\delta^{18}\text{O}$  values range from  $-6.6\text{‰}$  to  $-2.1\text{‰}$  (Supplementary material 2B). In each specimen, intra-tooth variation follows a sinusoidal pattern with amplitude ranging from 2 ‰ to 3.2 ‰ (Supplementary material 2C).

After modelling, the position ( $x_0$ ) of  $\delta^{18}\text{O}_{\text{max}}$  varies between 19.2 and 23.1 mm. The cycle period (X) varies between 24 and 35.1 mm (Supplementary material 2D). The  $x_0/X$  ratios (Supplementary material 2D) are plotted on a circular chart representing the annual cycle in Fig. 6. This reference set cannot be exploited for  $\delta^{13}\text{C}$  values because these sheep were fed maize (a  $\text{C}_4$  plant).

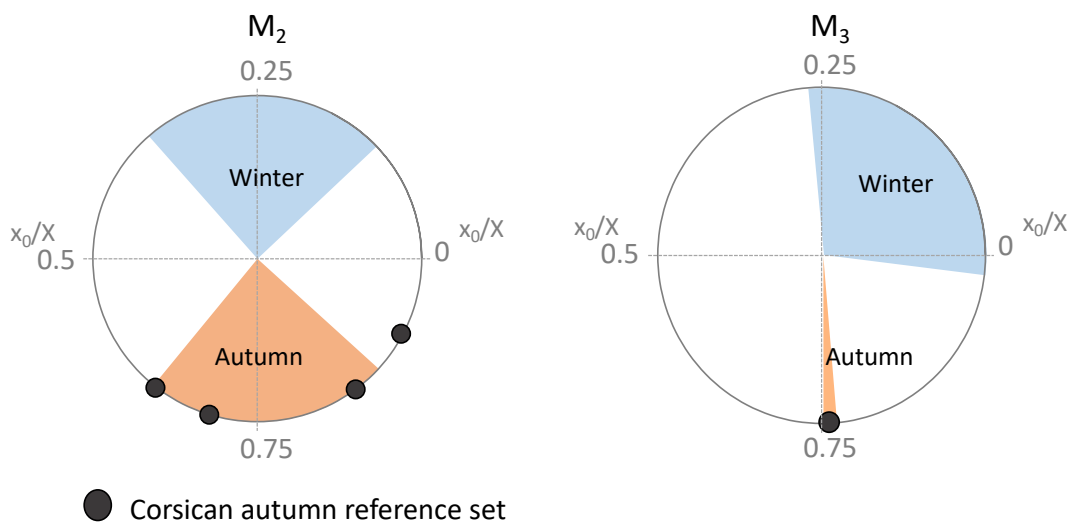


Fig. 6. Results from the Corsican sheep modern reference set. **A:** Position of the maximum  $\delta^{18}\text{O}$  value in tooth crown normalized by the cycle period ( $x_0/X$ ) in the second lower molars ( $M_2$ ) compared to the autumn (September and October births,  $N = 5$  in  $M_2$  and 1 in  $M_3$ ) reference set of Carmejane (Blaise and Balasse, 2011) and Selgua (Tornerio et al., 2018), and winter/spring reference sets (January to early April births,  $N = 15$  in  $M_2$  and 13 in  $M_2$ ) of Carmejane (Blaise and Balasse, 2011), Rousay (Balasse et al., 2012) and Kemenez (Balasse et al., 2020). **B:** Results from third lower molars ( $M_3$ ) compared to the Carmejane and Selgua winter reference sets and the Kemenez autumn reference set.

## 6.2.2. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences in archaeological sheep

The results are presented extensively in Supplementary material 4 to 6 and in Figs. 7 to 9. Intra-tooth variations in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values follow a sinusoidal pattern related to the seasonal cycle (Fig. 7 and Supplementary material 4B and 5B).  $\delta^{18}\text{O}$  values of the Araguina-Sennola sheep teeth range from  $-3.6\text{‰}$  to  $1.4\text{‰}$  (Supplementary material 4A) with intra-tooth amplitude ranging from  $1.4\text{‰}$  to  $3.6\text{‰}$  (Fig. 8 and Supplementary material 4B).  $\delta^{18}\text{O}$  values of the sheep from Montlaur range from  $-5.1\text{‰}$  to  $0.9\text{‰}$  (Supplementary material 5A), with intra-tooth amplitude ranging from  $1\text{‰}$  to  $4.1\text{‰}$  (Fig. 8 and Supplementary material 5B).

$\delta^{13}\text{C}$  values range from  $-13.4\text{‰}$  to  $-5.7\text{‰}$  at Araguina-Sennola, with intra-tooth amplitude ranging from  $1.1\text{‰}$  to  $7.2\text{‰}$  (Fig. 8 and Supplementary material 4A). At Montlaur, values vary from  $-14.2\text{‰}$  to  $-6.9\text{‰}$ , with intra-tooth amplitude ranging from  $0.6\text{‰}$  to  $6.9\text{‰}$  (Fig. 7 and Supplementary material 5A). In some sheep, the highest  $\delta^{13}\text{C}$  values are above the threshold of  $-7.7\text{‰}$ , beyond which a mixed  $\text{C}_3$  and  $\text{C}_4$  plants diet should be considered: ARA Ovis 2  $\text{M}^3$  ( $-5.7\text{‰}$ ) at Araguina; BCM Ovis 20 ( $-7.6\text{‰}$ ), BCM Ovis 18 ( $6.9\text{‰}$ ) and BCM Ovis 6 ( $-7.5\text{‰}$ ) at Montlaur, to which BCM Ovis 17 may be added with a maximum value very close to the threshold ( $-7.8\text{‰}$ ).

At Montlaur, the  $-13.7\text{‰}$  threshold defined as indicating the consumption of forest resources is also attained in ten sheep: BCM Ovis 2, BCM Ovis 5, BCM Ovis 6, BCM Ovis 7, BCM Ovis 8, BCM Ovis 11, BCM Ovis 12, BCM Ovis 16, BCM Ovis 17 and BCM Ovis 18 with minimum  $\delta^{13}\text{C}$  values ranging from  $-14.2\text{‰}$  to  $-13.7\text{‰}$  (Supplementary material 5A).

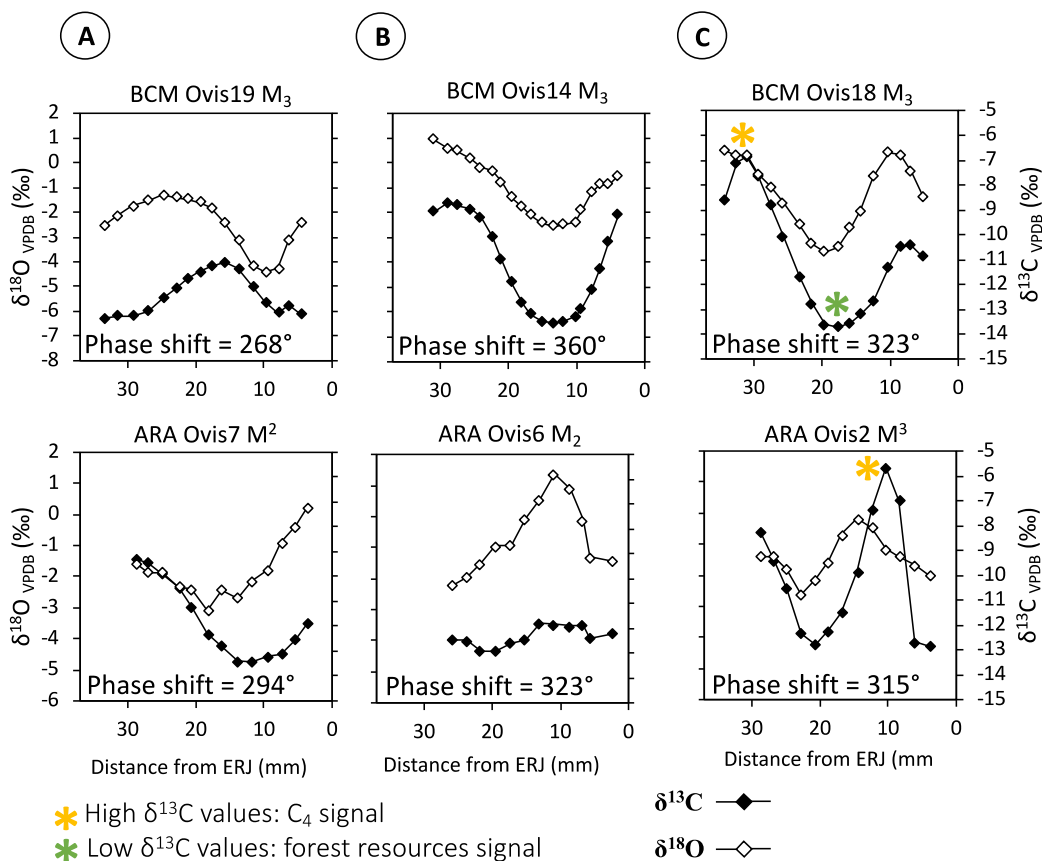


Fig. 7. Examples of results from sequential analysis of enamel stable oxygen and carbon isotope ratios at Araguina-Sennola and Montlaur. **A**: One example for each site of the greatest phase shift between the  $\delta^{18}\text{O}$  and the  $\delta^{13}\text{C}$  sequences. **B**: One example for each site of the smallest phase shift between the  $\delta^{18}\text{O}$  and the  $\delta^{13}\text{C}$  sequences. **C**: One example for each site of  $\delta^{13}\text{C}$  sequences presenting very high  $\delta^{13}\text{C}$  values in summer and very low  $\delta^{13}\text{C}$  values in winter.

### 6.2.3. Results from modelling

#### Modelling of $\delta^{18}\text{O}$ sequences.

Results from modelling are shown in Supplementary material 4C and 5C. Only solutions with a Pearson correlation coefficient  $\geq 0.91$  were retained (this excludes BCM Ovis 3). Sequences with a very low amplitude of variation (ARA Ovis 5), the absence of a sinusoidal pattern of variation (BCM Ovis 12), or the absence of a clear maximum (BCM Ovis 14, ARA Ovis 7), could not be modelled. Moreover, BCM Ovis 8 and BCM Ovis 16 were nearly but not fully complete (no ERJ). Consequently, although their  $\delta^{18}\text{O}$  sequences could be modelled, their  $x_0$  and therefore their  $x_0/X$  ratio are slightly underestimated. The position ( $x_0$ ) of the  $\delta^{18}\text{O}_{\text{max}}$  value varies between 3.1 and 16.1 mm at Araguina (Supplementary material 4C), and between 0.7 and 31.8 mm at Montlaur (Supplementary material 5C). The cycle period ( $X$ ) varies between 19.1 and 37.6 mm at Araguina and between 21.0 and 38.1 mm at Montlaur, reflecting variability in tooth size and highlighting the need to normalize  $x_0$  distances by  $X$ . The  $(x_0/X)$  ratios are plotted on circular charts on Fig. 8B and 8C for Araguina and Fig. 9B and 9C for Montlaur. The  $x_0/X$  ratio varies from 0.41 to 0.71 in the  $M^3$  and is 0.55 in the  $M_2$  at Araguina, while it varies from 0.02 to 0.99 at Montlaur (Supplementary material 4C and 5C).

Results from the modelling of the phase shift between  $\delta^{18}\text{C}$  and  $\delta^{13}\text{O}$  sequences are presented in Fig. 7 and Supplementary material 6, and show a phase shift ranging from  $268^\circ$  to  $365^\circ$ . The ARA Ovis 5 and BCM Ovis 12 sheep could not be modelled because the amplitude of  $\delta^{13}\text{O}$  variation is too small.

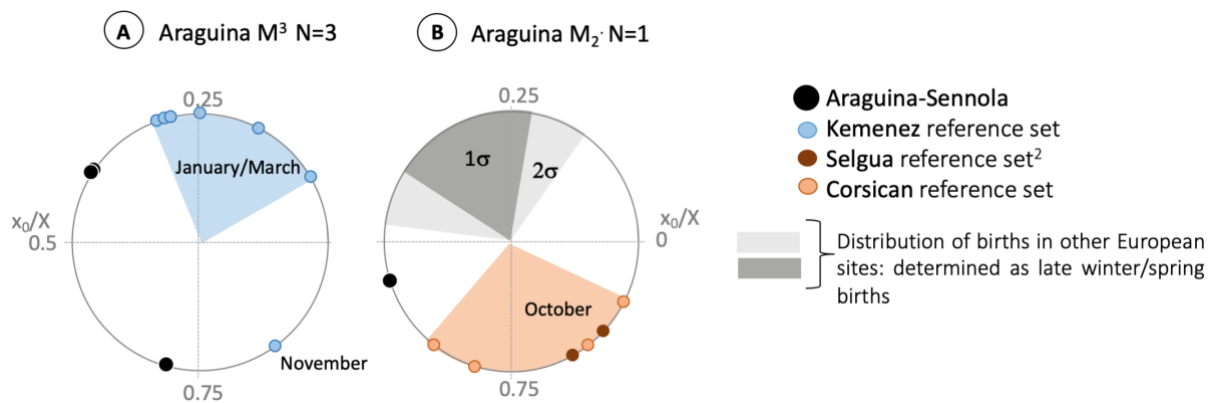


Fig. 8. Distribution of sheep births at Araguina-Sennola. A: Modelled results from third superior molars ( $M^3$ ) compared to the Kemenez reference set (Balasse et al., 2020). B: Modelled results from second inferior molars ( $M_2$ ) compared to the Selgua reference set (Torenero et al., 2018) the new Corsican reference set and others European Neolithic sites (Balasse et al., 2020).

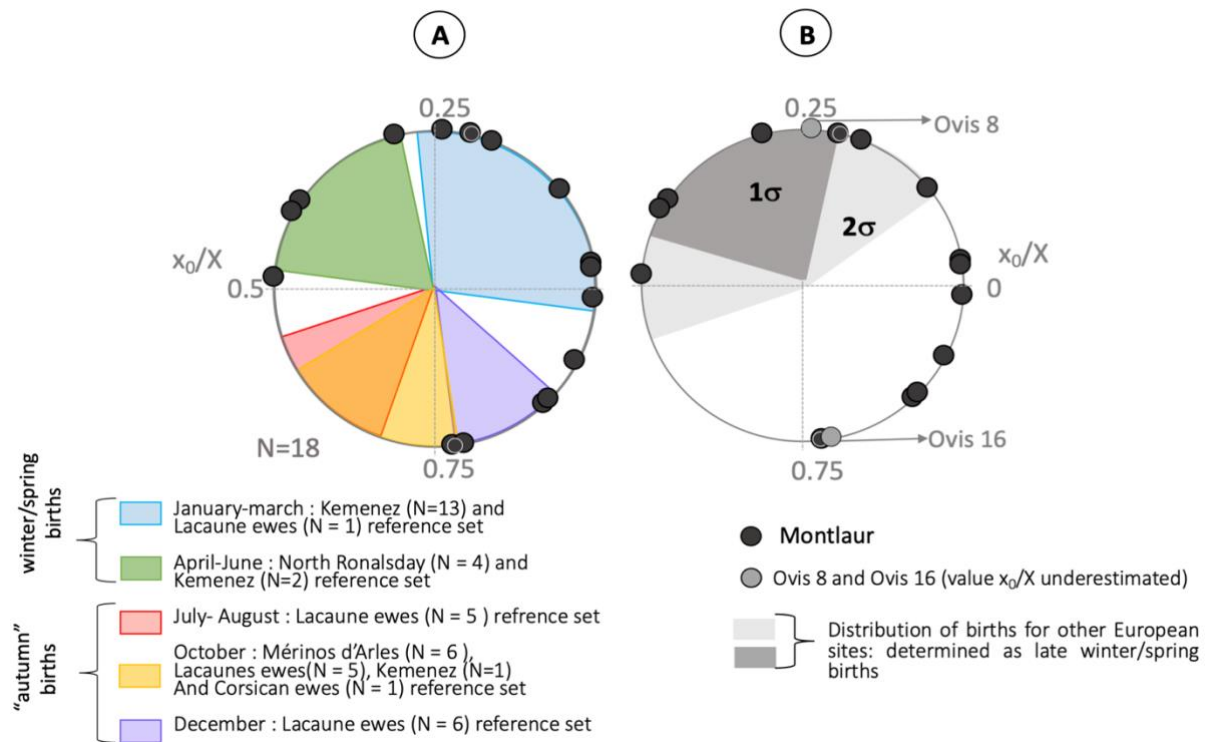


Fig. 9. Distribution of sheep births at Montlaur. **A**: Modelled results from third inferior molars ( $M_3$ ) compared to the Corsican new reference set and preexisting reference sets (Balasse et al., 2023). **B**: Comparison with others European Neolithic sites.

## 7. Discussion

### 7.1. Demographic management and farm orientation

#### 7.1.1. Demographic management oriented towards mixed production

Correspondence analysis results show a slight but indisputable diversity of profiles, organized along a gradient between high relative proportions of old (class HI) and very young (class A) animals (Fig. 5). Araguina Middle and Late Neolithic, Montlaur and the two reference profiles of Terrina IV and Cala Barbarina plot in the middle of the gradient, together with the subadult and adult age classes (B, C, D, E-F, G). According to Helmer et al. (2007) and Vigne and Helmer (2007), they suggest a poorly specialized culling strategy targeting young lambs (3–6 months) that would have reduced the ewes’ milk yield. Weaned lambs (6–12 months) and young adults (1–2 years) would have been killed for tender meat along with adults, including culled females because of their infertility or decreasing milk production. This strategy is very similar to the one observed at most northwest Mediterranean Neolithic sites (Blaise et al., 2010; Debono-Spireti et al. 2016; Gerbault et al., 2016) and suggests mixed milk and meat exploitation (Helmer, 1991, 1992; Helmer and Vigne, 2004). Thus, we can hypothesize that the lifestyle of these Neolithic populations did not target a single product, but relied rather on the optimization of all the animal resources from a herd. Furthermore, the mortality profile of Montlaur demonstrates almost five centuries of continuous demographic management oriented toward mixed milk and meat production.

Two datasets are exceptions to this. The Final Neolithic of Araguina (ARA 4, Fig. 3) plots together with the HI age class and therefore presents a relatively high proportion of very old animals. This may correspond to the exploitation of hair (wool did not yet exist in Europe in the Final Neolithic, Helmer, 1992; Vigne and Helmer, 1999; Helmer and Vigne, 2004), to the conservation of reproductive males, or to mouflon hunting. Indeed, the Corsican mouflon derives from neolithic sheep returned to the wild (Poplin, 1979; Vigne, 1988; Hiendleder et al., 2002; Chessa et al., 2009). and may not be easily distinguished from domestic sheep using morphological criteria. However, we cannot exclude a stochastic effect, since the sample is the smallest one of our corpus (MNI = 19).

The Early Neolithic profile at Araguina (ARA 1, Fig. 3) is particularly interesting, plotted together with the youngest classes A and B. This kill-off pattern presents a clear deficit of mature adults (classes EF and older)

since the high representativeness of class C and even more so of class D, which jointly account for 36%, indicates that these animals were slaughtered as soon as they reached adulthood, which is characteristic of tender meat consumption. This points to a flock with too few ewes to be sustainable for more than several generations. We can hypothesize that this truncated profile (*sensu* Vigne and Helmer, 2007) results from sporadic occupation and might be a sheepfold cave during this first phase of Neolithic occupation of the site. This interpretation is consistent with previous observations (Lanfranchi and Weiss, 1977; Vigne, 1988). On the other hand, during the Middle and Late Neolithic, throughout the fourth millennium BC, mortality profiles indicate the presence of all classes, corresponding to complete herd exploitation on the site (ARA 2 et 3, Fig. 3), while archaeological data also show the construction of a double-sided wall to maximize the shelter. These elements support the idea of a much more permanent occupation of the site (Lanfranchi and Weiss, 1977).

## 7.2. Reconstructing birth seasons

### 7.2.1. A new Corsican reference set

The results from modern Corsican sheep born in October were compared with the previously published modern sheep dataset (Fig. 6). The  $M_2$  results plot opposite the Rousay reference set for winter births (Balasse et al., 2012) and beside the autumn reference sets of Carmejane (Blaise and Balasse, 2011) and Selgua (Tornerio et al., 2018). The  $x_0/X$  ratio from the only  $M_3$  also plots on the edge of the quadrant opposite the reference set of Kemenez (Balasse et al., 2020). This new reference set increases pre-existing reference data for autumn births and shows good agreement between these different reference sets despite the use of different sheep breeds.

### 7.2.2. Lambing seasons at Araguina-Sennola and Montlaur

The results obtained at Araguina-Sennola and Montlaur were compared with modern references (Fig. 8A and 8B, Fig. 9A) and with previously published datasets for Neolithic Europe (Fig. 8B and Fig. 8B). At Araguina, the dataset is scattered over several periods of occupation from the Early to Final Neolithic. The data obtained from three  $M^3$  suggest that two sheep births (from the Early and the Middle Neolithic) occurred outside the winter period (defined by the Kemenez modern reference), probably in the spring, and a third one (from the Middle Neolithic) occurred in autumn (in the opposite season to the Kemenez reference) (Fig. 8A). The data obtained from one  $M_2$  (from the Final Neolithic) plots between the winter/spring and the autumn reference sets, and possibly corresponds to a summer birth (Fig. 8B). However, the limited size of this dataset rules out any further conclusions. We can only note that among these few births, some occurred outside the distribution usually encountered in more northern European sites (Fig. 8B).

The Montlaur dataset is one of the largest documented to date with 18 modelled individuals out of the 21 sampled remains. Births are spread over a large part of the year (Fig. 9): nine births (Ovis BCM 4, 8, 9, 10, 13, 17, 18, 20 and 21) plot within the lambing period centred in the spring found at higher latitude sites in Europe; while nine others occurred outside this period and extend from autumn to early winter (Ovis BCM 1, 2, 5, 6, 7, 11, 15, 16, 19) (Fig. 9B). This assemblage thus presents as many spring births as autumn births. These autumn births are nearly absent from more northern European sites (Balasse et al., 2020), but they have already been observed in the north-western Mediterranean region at Early Neolithic sites (Gazel and Tai, both in Languedoc, southern France, Tornerio et al., 2020) and at the Middle Neolithic site of Auriac (Languedoc, southern France), which is contemporary with Montlaur (4000–3800 BCE, Fabre et al., 2021). Today, these autumn lambing systems, typical of the north-western Mediterranean, involve the implementation of three parameters: (i) a physiological capacity for 'out-of-season' breeding; (ii) scheduling by herders, involving the management of sheep socio-sexual relationships; (iii) sustainability ensured by the availability of grazing resources during lactation in autumn (Tornerio et al., 2020). In present-day husbandry systems, a predominant lambing season in autumn is always backed up by secondary lambing in the spring, due to 'catch-up' mating in the autumn if spring fertility was low. The occurrence of spring births alongside predominant autumn lambing was observed at Auriac (Fabre et al., 2021). At Montlaur, the predominance of autumn births cannot be confirmed, as autumn and winter-spring births are equally represented. In fact, the morphology of the zooarchaeological assemblage of Montlaur is also heterogeneous, with significant variations in bone size (as observed by one of us: V.F.), which could suggest different origins for these sheep. Perhaps the reason for such a composite assemblage lies in trading activities at the site of Montlaur? Indeed, given its position at the very south of the island, so close to Sardinia



and opening onto the sea, Montlaur could have been a very strategic trading point. This assemblage could also reflect a livestock market. On the other hand, the sheep mortality profile displays all age classes, testifying to a local exploitation of complete herds, rather than animals for trade. Currently, the location of dwellings around the domestic activity area and the large excavated landfill has not been recovered yet. As the function of Montlaur remains uncertain, the interpretation of its faunal assemblage also remains incomplete, since we do not know whether it results from a perennial and local community, or from several communities interacting during regular or exceptional meetings. Nonetheless, our results confirm the co-existence of two lambing seasons in this Late Neolithic site at the interface between Sardinia and Corsica, and further demonstrate the ability of Western Mediterranean sheep to breed out of season.

### 7.3. Exploitation of the surrounding landscape

Pre-industrial livestock caprine farming systems in Corsica involved seasonal herding between high mountain pastures in summer and coastal plains in winter, with intermediate stays at mid-altitudes in forested areas (Ravis-Giordani, 1983). Such a mobility scheme would presumably lead to varying  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  sequences in opposite phases, with a significant  $\text{C}_4$  plant component in coastal plains marking the winter signal, and the absence of this  $\text{C}_4$  component from higher elevation pastures in summer. This pattern has been observed in modern sheep herding from the Ebro valley to the Pyrenees (Tornerio et al., 2018). Furthermore, depending on the duration of intermediate stops in forested areas, a canopy effect signal could result in increased and more complex variations in  $\delta^{13}\text{C}$  values. In the Early to Final Neolithic sheep from Araguina-Sennola and Montlaur, the pattern of co-variation of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  sequences does not fundamentally differ from that observed in sheep fed year-round on the same grazing areas (Balasse et al., 2019). However, this does not preclude seasonal changes in diet or pasture areas. It just so happens that the seasonal occurrence of these different food sources contributes to seasonal changes in the signal in the same way as it would on a local scale (higher  $\delta^{13}\text{C}$  values in summer, lower in winter).

Moreover, the high interindividual variability in  $\delta^{13}\text{C}$  values reflects high variability in the degree and patterns of mobility (Fig. 10). Such strategies suggest increased flexibility to face variations in forage availability. It demonstrates how the herders have been able to adapt the animals to the contrasting and seasonal resources of this Mediterranean island territory. The pattern of variation of  $\delta^{13}\text{C}$  values measured in sheep enamel suggests seasonal changes between at least two dietary poles: the consumption of plants from open areas, including in some instances  $\text{C}_4$  plants (higher  $\delta^{13}\text{C}$  values) in the summer, and forest resources (lower  $\delta^{13}\text{C}$  values) in winter. We demonstrated the consumption of  $\text{C}_4$  plants for one sheep at Araguina-Sennola and at least four sheep in Montlaur. However, other individuals may also have consumed  $\text{C}_4$  plants, albeit in lower proportions, if we take into account the duration of tooth enamel mineralization resulting in the attenuation of the intra-tooth amplitude of variation. Nowadays,  $\text{C}_4$  plants only represent a very small percentage of plant species in Corsica but some of them are native (Collins and Jones, 1985). They could possibly have been preferentially consumed in coastal zone salt marshes (Revelles et al., 2019), as  $\text{C}_4$  plants are adapted to drought stress (Chmura and Aharon, 1995; Tanner et al., 2007). Moreover, they are not found in closed environments and are not expected in high altitude grassland (such as Plateau du Coscione, at 1500 m, currently used as a summer pasture by the shepherds of the south of the island). Hence, it is unlikely that sheep with a  $\text{C}_4$  plant signal spent the summer on highland meadows.

Furthermore, out of the 21 sheep analysed in Montlaur, ten fed on plants growing under a forest canopy during winter (Fig. 10 and Supplementary material 5A and 5B), while two others show winter  $\delta^{13}\text{C}$  values close to the  $-13.7\text{‰}$  threshold. The latter could have seasonally consumed lower proportions of forest resources (Ovis 14  $\delta^{13}\text{C}_{\text{max}} = 13.5\text{‰}$ ; Ovis 19  $\delta^{13}\text{C}_{\text{max}} = 13.3\text{‰}$ ). These sheep show a physiological aptitude for autumn lambing, but nutrition remains a determinant

parameter for successful reproduction (Robinson, 1990; Gunn et al., 1991; O'callaghan and Boland, 1999). The consumption of forest plants in winter could be directly linked to the food supply requirements of milk exploitation, to support mating and lactation periods. Autumn lambing may require dietary supplements in winter to favour milk production and maintain a good weight for spring mating (Tornerio et al., 2020). Paleoenvironmental reconstruction at Piantarella provided evidence for a predominantly open landscape at the time of the Late Neolithic Montlaur occupation (Revelles et al., 2019). However, this does not exclude the presence of locally dense forest patches which could have been used as fodder. Alternatively, sheep herds could have been taken to forest-dominated areas during winter. At this stage, it is not possible to determine whether the canopy signal derives from the consumption of fodder harvested by the farmer (in which case herds could remain static) or from grazing in a closed environment (which would involve herding in the forest).

## 8. Conclusions

Until recently, Araguina-Sennola was the only faunal dataset for the Neolithic period in the Bonifacio region since its excavation in the 1970 s. The discovery of the large assemblage of faunal remains of Montlaur opened new opportunities. At Araguina-Sennola, the caprine mortality profile reveals changes throughout almost 2500 years of occupation, from a sporadic camp to a more permanent habitat. Caprine demographic management at Montlaur remained constant for the five centuries of occupation during the fourth millennium BC, and is similar to the pattern observed at Araguina-Sennola for the same time period. The four available Corsican Neolithic datasets for caprine demographic management (Araguina-Sennola, Montlaur, Terrina IV and Cala Barbarina) display mixed exploitation oriented towards milk and meat production, as is observed in other north-western Mediterranean Neolithic sites.

The occurrence of autumn lambing in the Middle Neolithic at Araguina-Sennola, and autumn births coexisting with similar proportions of winter/spring births at Montlaur in the Late Neolithic confirm the existence of sheep with a physiological capacity for out-of- season breeding at that time in the western Mediterranean area, as previously shown by other studies (Tornero et al., 2020; Fabre et al., 2021). At this stage, we cannot determine how these different birthing seasons (spring/autumn) were combined at Montlaur, whether they co- occurred within the same herds and were thus strategically scheduled to spread out animal products over the year, or whether they resulted from several farms complementing each other on a regional scale. In all cases, they seem to have coexisted in systems in communication with each other.

Regarding the exploitation of the herding territory, the C<sub>4</sub> signal observed in a number of individuals at Araguina-Sennola and Montlaur does not argue for the use of high mountain pastures in summer, although this cannot be excluded for all sheep. The location of these C<sub>4</sub> plants is unknown, however the most likely explanation would be that they were found in salt marshes, suggesting that sheep spent the summer in coastal plains. The exploitation of densely forested areas for pastoral purposes is established, although it is not possible to determine whether tree branches were collected and supplied as fodder, or if sheep pastured in the forest. If forest pasturing effectively took place, given the pre- dominantly open immediate local landscape, animals would have been herded towards inland and higher elevation areas in winter. Two birthing seasons and mobile herding in the Neolithic are echoed in the specificities of 20th century Corsican caprine husbandry (Delfosse and Prost, 1998) and testify to the strong adaptive capacity of these early farming societies to the north-western Mediterranean environment.

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### Declaration of Competing Interest

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

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2023.104037>.

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