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Sheep and goat management in the Early Neolithic in the Zagros region (8000–5000 BC): New zooarchaeological and isotopic evidence from Ganj Dareh, Bestansur and Jarmo

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ABSTRACT

The transition from hunter gathering to farming is one of the most important episodes in the history of humankind. Considerable evidence indicates that this shift was a slow, complex, highly localized process, which took place in multiple places in Southwest Asia independently, from around 9500 BC. Caprines were arguably the first domesticated livestock, brought under human control during a process that began in the 9th millennium BC in a region extending from south-eastern Turkey to north-western Iran. In this research we integrate zooarchaeological analysis with stable isotopic data of faunal remains from three key Early Neolithic sites in the Eastern Fertile Crescent: Ganj Dareh (ca. 8000 BC), Bestansur (ca. 7800–7000 BC) and Jarmo (ca. 7000–5000 BC).While some form of goat management seemed to have been practiced at Bestansur, based on spherulites, dung and shed deciduous teeth, no evidence has been found for winter foddering or transhumance practices. At Ganj Dareh goat were managed, and might have been foddered during the winter or vertical transhumance might have taken place. At Pottery Neolithic Jarmo both sheep and goat were managed and they were possibly brought to higher elevations during the summer months or foddered during winter. This research has supported the idea that already during early stages of goat management, humans kept a high degree of control over the population.

1. Introduction

The transition from hunter gathering to farming is one of the most important episodes in the history of humankind. Considerable evidence indicates that this shift was a slow and complex process, which took place in multiple places in Southwest Asia independently, from around 9500 BC, rather than a sudden revolutionary change subsequently spreading from a single core zone (Fuller et al., 2011; Zeder, 2011). Initial management strategies, especially of animals, were developed several millennia before the first detectable changes in skeletal morphology related to domestication (Zeder, 2011, 2012). In addition, management, domestication and adaption of the different livestock and plant species were highly localized processes, influenced by both cultural and environmental factors (Fuller et al., 2011; Arbuckle and Atici, 2013; Arbuckle, 2014).

Caprines were arguably the first domesticated livestock, brought under human control during a process that began in the 9th millennium BC in a region extending from south-eastern Turkey to north-western Iran (Naderi et al., 2008; Zeder, 2011; Daly et al., 2018). Both sheep and goat were a major food source for humans throughout the Palaeolithic and Epipalaeolithic in the Eastern Fertile Crescent (Zeder, 1999; Matthews et al., 2013) and continued to be of major dietary importance in the Neolithic (Zeder, 2008). The lack of morphological markers in the first stages of domestication makes it challenging to evaluate when people first started to manage caprines and what these first stages of animal management specifically involved (Arbuckle and Atici, 2013). During the early phases of management, humans may have started to control diet and movement, as well as changing their way of selecting animals for slaughter. The intensive culling of young males is evident in some areas at the start of goat herding in the Zagros Mountains (Zeder, 2008). However, clear evidence for young male kill-off appears considerably later than the origins of caprine management in the faunal record in Southwest Asia overall (Arbuckle and Atici, 2013; Arbuckle, 2014). Instead, early Neolithic caprine management practices were

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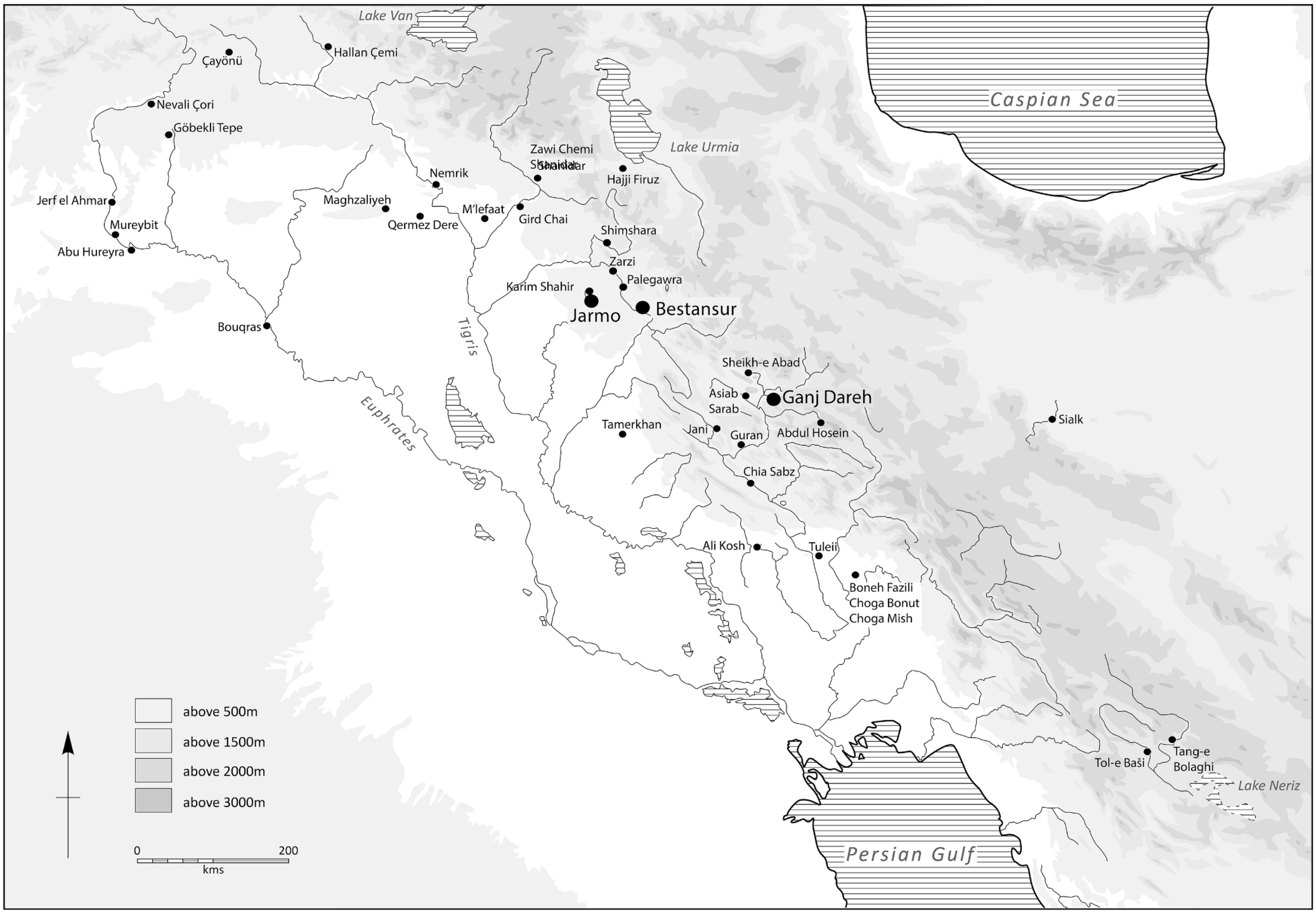

Fig. 1. Map showing Neolithic sites in the Zagros region.

characterized by a high degree of local diversity. Foddering, control over mobility, penning and manipulation of weaning age need to be investigated to obtain a clearer picture of early animal management (Arbuckle and Atici, 2013; Stiner et al., 2022). In this research, we integrate zooarchaeological analysis with stable isotopic analysis of faunal evidence from three key Early Neolithic sites in the Eastern

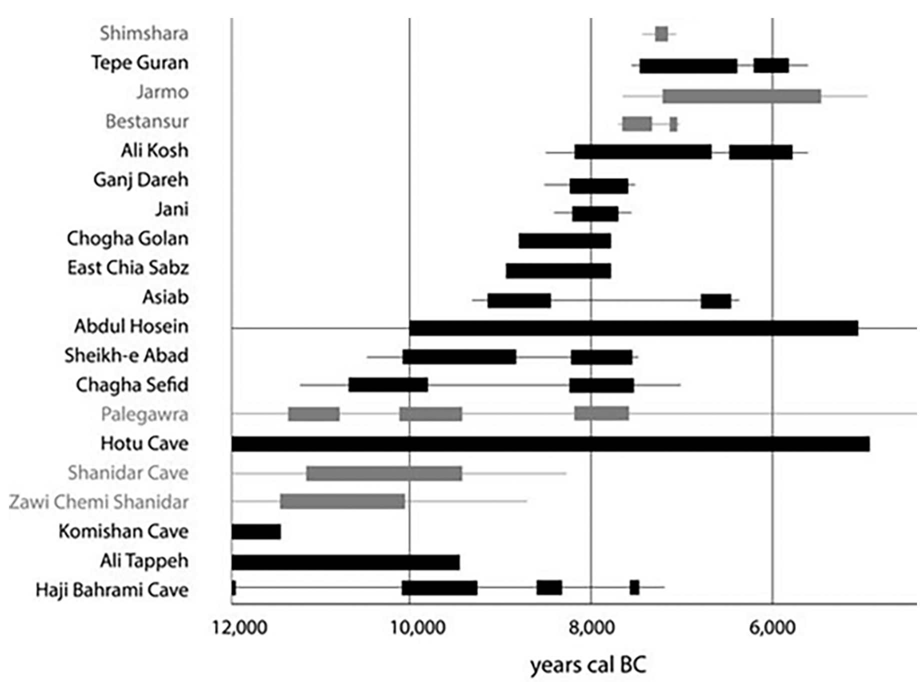

Fig. 2. Chronological profile of the sites in the Zagros region, sites in Iraq in grey and Iran in black (after Matthews and Fazeli Nashli, 2022: Fig. 5.2).

Fertile Crescent: Ganj Dareh (ca. 8000 BC) (Zeder, 2008; Yeomans et al., 2021), Bestansur (ca. 7800–7000 BC) and Jarmo (ca 70000–5000 BC) (Zeder, 2008) (see Fig. 1,2), to investigate local variation and the early stages of caprine management.

2. Research context of studied sites

2.1. Ganj Dareh

Ganj Dareh is a small mound site in the high Zagros Mountains at ca. 1400 m above sea level, in western Iran (Fig. 1). The site was first excavated in the 1960 s and 1970 s and has been restudied (Zeder, 2008) and re-excavated over the last decade (Darabi et al., 2019). The site consists of multiple levels, and was inhabited for a total span 100–200 years. Goats are the most abundant animals in all levels, outnumbering sheep 15:1 (Zeder, 1999). Apart from caprines, the zooarchaeological assemblage contains wild boar, hare, deer, aurochs and various birds. Evidence of crab, crayfish and land snail consumption is present (Hesse, 1978). The presence of house mouse (*Mus musculus)* has been argued to support year-round occupation (Hesse, 1979). Morphologically domestic barley has been argued to be present on site (Van Zeist et al., 1984). The carbonised plant remains from the re-excavation are poorly preserved, making it impossible to determine their domestic status (Merrett et al., 2021).

2.2. Bestansur

Bestansur is a Neolithic site located in the foothills of the Zagros Mountains at 550 m above sea level, in Iraqi Kurdistan (Fig. 1). The site has been excavated since 2012 over the course of nine field seasons by a team from the University of Reading in collaboration with the Sulaimaniyah and Erbil Directorates of Antiquities and Heritage. The site covers about 4 ha and the top of the mound is 8 m high, although on the edges of the site the Neolithic is only 30–50 cm below modern plough depth (Richardson et al., 2020, 116). Neolithic occupation spans from ca. 7800–7000 BC (Fig. 2), with Neolithic layers at least 4 m thick (Matthews et al., 2020, 629), in places covered by significant occupation of Iron Age and later date (first millennium BC). The site is situated close to a variety of ecosystems comprising springs, flat steppe, river and marshlands, in the foothills of the Zagros, all of which would have been accessible for the inhabitants of the Neolithic site (Matthews et al., 2020, 633). Apart from caprines, wild boar and large cervid are very abundant at the site (see SI; Bendrey et al., 2020; De Groene et al., 2021).

2.3. Jarmo

Jarmo is a 1.3 ha Neolithic site located in the foothills of the Zagros Mountains, at ca. 800 m above sea level, in Iraqi Kurdistan (Fig. 1). The exact dating of Neolithic Jarmo is problematic because of lack of datable material, including poorly preserved bone collagen and issues with the stratigraphy (Price and Arbuckle, 2015, 444) but the site has both Early Neolithic and Pottery Neolithic layers, and so is likely to span ca. 7000-5000BC (Fig. 2). The site was excavated over the course of three field seasons between 1948 and 1955 (Braidwood and Howe, 1960), and the zooarchaeological assemblage has since been reanalysed (Flannery, 1983; Stampfli, 1983; Price and Arbuckle, 2015; Zeder, 2008). In both Early Neolithic and Pottery Neolithic periods, goat were the dominant taxon, followed by sheep. Pigs, aurochs, gazelle, deer, hemiones, fox, dog, lion, leopard, lynx, badger and hare remains were also recovered (Price and Arbuckle, 2015).

3. Methods and material

3.1. Material

In this study, we analyse the zooarchaeological material recovered from Bestansur during all field seasons up until 2021, integrating previously published and new data (Bendrey et al., 2020; de Groene et al., 2021, see these reference for further description of excavation methods). We use the demographic and biometric data of Ganj Dareh and Jarmo published by Zeder and Hesse (2000) and Zeder (2008). We sampled a total of 10 molars from Pottery Neolithic Jarmo and 18 molars from Ganj Dareh for sequential carbon and oxygen isotopic analysis of tooth enamel, which have not been part of any other studies. Eight molars from sheep/goat from Bestansur were previously sampled at the University of Reading and one molar from Bestansur was sampled for this study. Both M2 and M3 from the mandible were sampled, because of the limited availably of undamaged teeth, but only one molar per animal was sampled. All sampled molars from Jarmo derived from the Pottery Neolithic layers. All archaeological molars could be from either sheep or goat, since it is unreliable to distinguish molars of sheep/goat morphologically (Zeder and Pilaar, 2010). The number of samples taken per teeth varies, since some teeth had taphonomic damage to the enamel but these places on the teeth were avoided when taking samples. We tried to take at least 10 samples per molar (SI). One molar of modern sheep from the modern village Bestansur was also sampled. In the recent past sheep in this village were kept in the foothills of the mountains during spring, fallow fields in the summer, and at the village in the winter (Bendrey et al., 2016). However, with the construction of a road, access to the fallow fields in alluvial floodplains became restricted and caprines are now kept around the village all year (Elliott et al., 2015), so this tooth would give a local signal.

3.2. Zooarchaeological methods applied on the Bestansur zooarchaeological assemblage

Sheep and goat are osteologically very similar, so the criteria of Boessneck et al. (1964) were used to identify cranial bones, and Zeder and Lapham's (2010) criteria were used to distinguish post-cranial bones. When separation was not possible the bones were categorised as sheep/goat. No attempt was made to distinguish sheep and goat molars, since it has been shown to be unreliable (Zeder and Pilaar, 2010). All possible anthropogenic modifications to the bones as well as pathologies were recorded. Butchery marks were recorded following Binford (1981) and when necessary extra information was added. Measurements of the bones were taken following Von den Driesch (1976). Mortality profiles have been assessed based on bone fusion. Postcranial fusion ages from Zeder (2006) were followed for sheep and goat, since this system is based on caprines from the Zagros region. The assemblage consisted of few mandibles suitable for a dentition-based mortality profile, so this approach is not included. To investigate possible young male kill-off, biometric data are used in addition to fusion-based mortality profiles. Goat exhibit a relatively high degree of sexual dimorphism and sheep are sexually dimorphic as well, although to a lesser extent (Zeder, 2008). Therefore, male and female caprines can be distinguished based on the measurements of the long bones (Zeder and Hesse, 2000). Considering the modest size of the dataset, the LSI (Logarithm Size Index) method is used to get a richer understanding of the size of the animals and the sex pattern. The LSI uses $\log_{10}$ of the ratio between the measurement and its standard (Meadow, 1999), which makes it possible to compare different elements, maximising the dataset available for comparisons. The standards which are published and commonly used in Near Eastern archaeology are the average measurements of goat from the Taurus mountains (Uerpmann and Uerpmann, 1994) and modern wild sheep from Kermanshah Iran (Zeder, 2008, 263). Depth and breadth measurements are most influenced by sexual dimorphism (Zeder, 2008), so those are plotted in the LSI diagrams. Skewness and kurtosis have been used to describe the shape of LSI diagrams (Arbuckle and Atici, 2013, 223). The kill-off of young males is expected to be identified in results in the LSI data (Zeder, 2008). A characteristic distribution for young male kill-off exhibits strong positive skewing (with a tail on the right of the mean) and positive kurtosis (leptokurtic or 'peaked' distribution shape) (Arbuckle and Atici, 2013, 223). In the LSI graphs unfused and fused elements are represented as well as the astragalus, which does not fuse. In scenarios where young male-cull was practiced, larger unfused elements are likely to be represented in the LSI graph. Elements which fuse before 18 months are indicated in a different colour than elements which fuse after 18 months, since the elements which fuse before 18 months could be representing animals which were slaughtered at a young age as well as animals which survived into maturity, while elements which fuse after 18 months represent animals which certainly survived into maturity.

3.3. Isotopic analysis

The diet and movement of the caprines was investigated using sequential stable isotope analysis of carbon and oxygen in tooth enamel carbonate. Stable isotopic analysis of tooth enamel of domestic and non-domestic animals has already improved our understanding of animal management (Balasse et al., 2002; Balasse et al., 2003; Balasse et al., 2006) in the Levant (Makarewicz, 2017; Tornero et al., 2016) and Anatolia (Henton, 2012; Makarewicz et al., 2017). Bezoar goat, the wild progenitor of domestic goat, preferred habitats are mountainous areas with a mix of rocky outcrops and vegetation. They can survive very well in relatively arid areas but can live in forests too (Weinberg et al., 2008). The bezoar goat is herbivorous and relies on both browsing and grazing, although they prefer the former to the latter (Dywer, 2017). They can obtain part of their water intake from leaf waters (Weinberg et al., 2008; Dywer, 2017). The habitat ranges of bezoar goat and wild sheep overlap but in general wild sheep live in lower mountain ranges and foothills, while bezoar goat live at higher altitudes (Uerpmann, 1987; Zeder, 2006). Similar to wild goat, wild sheep both browse and graze (Valdez and DeForge, 1985). In contrast to goat however, they are more adapted to grazing and cannot cope with long periods without drinking water (Dywer, 2017). Nowadays in the Zagros Mountains, wild goats seasonally migrate (Al-Sheikhly et al., 2020). Wild sheep migration, however, is dependent on food availability and shelter (Dywer, 2017), so it is possible that, in the past, wild sheep stayed local in the foothills of the Zagros Mountains.The carbon isotopic composition of the bioapatite of herbivores is determined by the $\delta^{13}C$ values of ingested plant foods (Balasse, 2002). In plants, apart from photosynthetic pathways (C_3 and C_4 plants), the $^{13}C/^{12}C$ ratio in plant tissues is dependent on light intensity, temperature, humidity, moisture availability and recycling of CO_2. Variation between the isotopic ratios occurs within species and

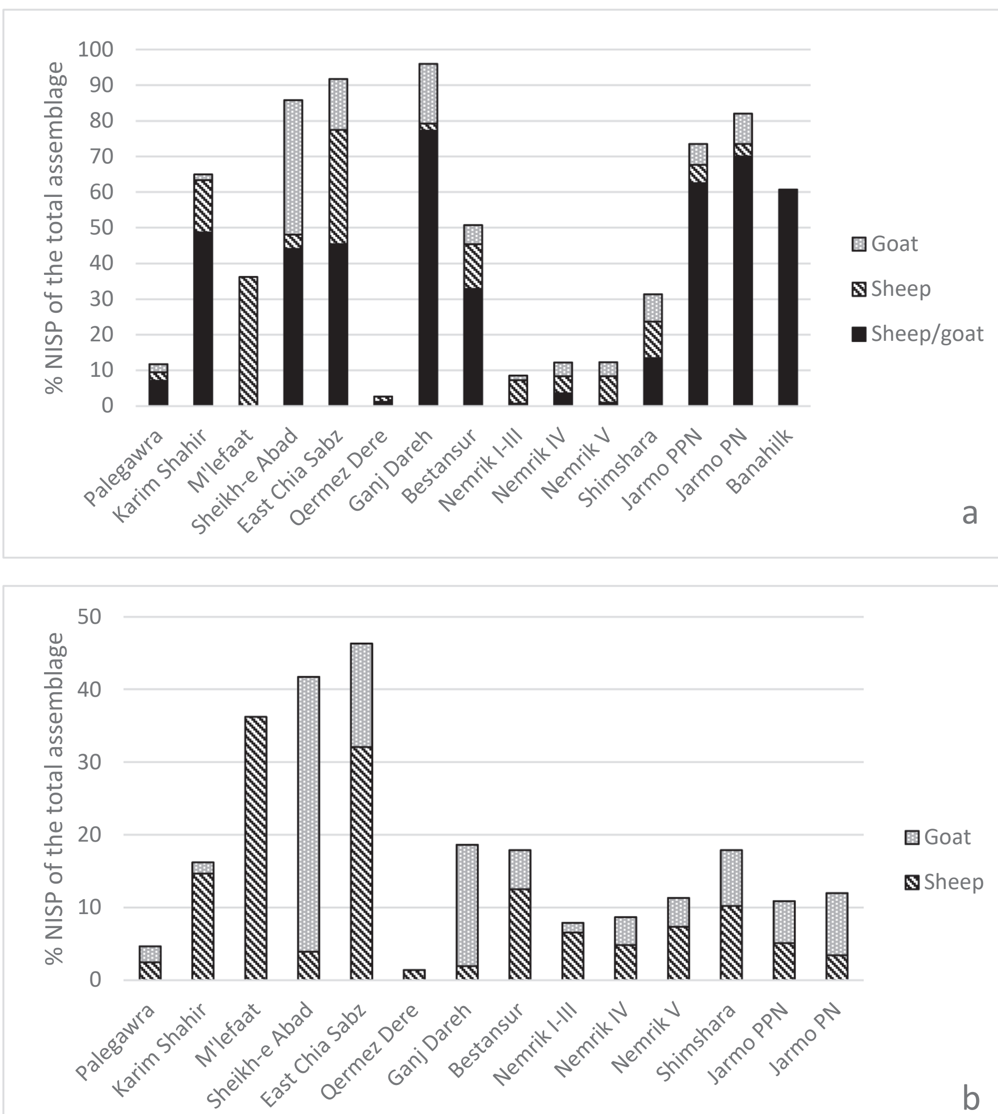

Fig. 3. Fig. 3a the percentage of sheep and goat at Epipalaeolithic and Neolithic sites in the Zagros region, including sheep/goat, Fig. 3b. The percentage of sheep goat of all identified mammals at Epi-Palaeolithic and Neolithic sites in the Zagros region, (see supplementary information for NISP, dating and references).

plant tissue; C_3 plants display $\delta^{13}C$ ranges from 37 − 20‰ (average: −27‰) and C_4 plants are 21-9‰ (average: − 12‰) (Heaton, 1999; Farquhar et al., 1989; Lee-Thorp, 2008). Differences in $\delta^{13}C$ in C_3 biomes vary according to environmental conditions. On a seasonal basis in semi-arid environments the $\delta^{13}C$ in C_3 plants shifts according to changes in moisture availability, humidity levels, and night-time temperatures. The carbon isotope composition of C_3 grasses is heavily dependent on water availability (Heaton, 1999). In periods of drought, grasses tend to conserve water by closing their stomata, the microscopic pores on leave epidermis regulating transpiration and CO_2 uptake (Chaves et al., 2016). Consequently, less CO_2 from the air will be taken up during dry periods and leaves will get enriched in $\delta^{13}C$ (Heaton, 1999). Nowadays, in the Zagros region, C_4 plants mainly occur locally in saline zones, which are common in semi-arid environments except for the southern Zagros, where C_4 grasses are generally abundant (Bocherens et al., 2000). The abundance of C_3 and C_4 plants varies between seasons and altitude as well with increased abundance of C_4 plants on lower altitudes and during the summer months (Hatami and Khosravi, 2013). For sheep and goat, the precise carbon isotope fractionation between diet and tooth enamel bioapatite is unknown, but a fractionation value of around 14.5‰ obtained from modern cattle on a controlled diet (Passey et al., 2005) is normally applied (Makarewicz and Pederzani, 2017, 2-3), although the level of fractionation between diet and bioapatite for sheep varies based on diet (Cerling and Harris, 1999; Zazzo et al., 2010). Within the paper we do not apply fractionation value in the data presentation. Oxygen is assimilated in animal tissue from ingested water and oxygen in food. Oxygen isotopic composition of meteoric water is influenced by continental positioning, rainfall amount, temperature, seasonality, humidity levels and altitude (Dansgaard, 1964). Oxygen isotope values are positively correlated with temperature, with an average increase of 0.6 ‰ values per increase in 1 °C in temperature, and negatively correlated with altitude, with an average decrease of 0.3 ‰ in meteoric values per 100 m increase in altitude (Poage and Chamberlain, 2001). The $\delta^{18}O$ of skeletal bioapatite is linked to the $\delta^{18}O$ of drinking water and plant water ingested by animals, so indirectly linked to meteoric water (Longinelli, 1984). Sequential isotopic analysis of M_2 and M_3s was carried out to explore seasonal differences in diet and possible seasonal movement of the caprines. Once fully mineralised the isotopic composition of teeth enamel does not change (Balasse, 2002). In sheep, M_2 crown development begins at 1 month and finishes at 12 months, while in the M_3, begins at 9–10 months and finishes at 20–22 months (Milhaud and Nezit, 1991; Zazzo et al., 2010). The main factor to influence $\delta^{18}O$ intra-teeth in the sampled populations variation is seasonality. Based on a model derived from a dataset of modern teeth, sinusoidal curves with ranges of >6‰ $\delta^{18}O$ intra- tooth have been suggested to imply strong seasonality, with cold and/or wet winters and hot summers with periods of drought (Henton, 2012, 3269). It has been argued that ranges smaller than 6‰ could indicate animals were escaping climatic extremes over the year (Britton et al., 2009, 1165), which in case of vertical transhumance would mean that animal would be on the cooler highlands during the summer months (Henton, 2012). Another possibility is that the sheep/goat stayed local during the year, but there were no extreme seasonal changes. It would be expected that the $\delta^{18}O$ peak and the $\delta^{13}C$ peak coincide if the animals were grazing and were not given ^{13}C enriched fodder during winter months, since during summer C_3 grasses get enriched in ^{13}C and C_4 plants are generally more abundant. If vertical transhumance was practiced, or if wild animals moved over vertical distances themselves $\delta^{18}O$ peak and the $\delta^{13}C$ peak would not coincide since fauna in higher altitudes is generally depleted in ^{13}C compared to the lower altitudes (Liu et al., 2016; Van de Water et al., 2002). So, intra-tooth relative higher $\delta^{13}C$ values coinciding with relative lower $\delta^{18}O$ could indicate vertical transhumance or winter foddering (Makarewicz, 2017, 17). Sample selection was based on teeth availability and permission for sampling. Since the Jarmo and Ganj Dareh specimens are museum specimens, sampling permission was given only for teeth which did not have to be broken out of the jaw.

Table 1
Fusion data of sheep, goat and sheep/goat of Bestansur (following fusion ages of Zeder, 2006).

Age of fusion months fusion **(Sheep)**	Element	Zeder age category	fused	unfused	fusing
0–6	Radius proximal	A	6		
6–12	Humerus distal	B	4		
12–18	Phalanx 1	C	10		
12–18	Phalanx 2	C	5		
18–30	Tibia distal	D	3	1	
18–30	Metacarpus	D	9	1	
18–30	Metatarsal	D	7		
30–48	Calcaneus	E	2	1	
30–48	Radius distal	E	3	1	
Age of fusion in months **(Goat)**	Element		fused	unfused	fusing
0–6	Radius proximal	A	2		
6–12	Humerus distal	B	4		
12–18	Phalanx 1	C	10	3	
12–18	Phalanx 2	C	1		
18–30	Tibia distal	D	1		
18–30	Metacarpus	D	2		
30–48	Radius distal	E	1		
Age of fusion in months **(Sheep/goat)**			Fused	Unfused	Fusing
0–6	Radius proximal	A	4		
6–12	Humerus distal	B	6		
6–12	Scapula	B	7	3	
6–12	Pelvis	B	1		
12–18	Phalanx 1	C	2	4	
12–18	Phalanx 2	C	10	2	1
18–30	Tibia distal	D	8		
30–48	Radius distal	E		2	
30–48	Ulna distal	E		1	
30–48	Femur proximal	E	1		
30–48	Femur distal	E	3		
30–48	Tibia proximal	E	4		
30–48	Calcaneus	E		2	
48+	Humerus proximal	F	1		

Samples for stable isotopic analysis were taken and processed at the University of Reading, School for Archaeology, Geography and Environmental Science, partly carried out by the lead author and partly for a master thesis project by Coogan. Sequential sampling was performed from the occlusal surface to the basis of the crown, perpendicularly to the tooth growth axis. Samples were taken using a diamond-coated drill, as evenly spaced as possible over the crown height and through the whole enamel thickness. The protocol for analysing the samples was adapted from Balasse et al. (2002), but involved only one acid step (Frémondeau et al., 2012). Samples of Bestansur taken by Coogan were pre-treated in dilutedH202 for 24 h and analysed at KU Leuven in the-Thermal Delta V Advantage Isotope Ratio Mass Spectrometer. Samples for this study were treated with acetic s 0.1 M, since research showed this does not change the isotopic composition of the tooth remains (Snoeck and Pellegrini, 2015; Pellegrini and Snoeck, 2016) and analysed at the University of Reading on a Thermo Scientific Delta Plus Isotope Ratio Mass Spectrometer coupled to a GasBench II.

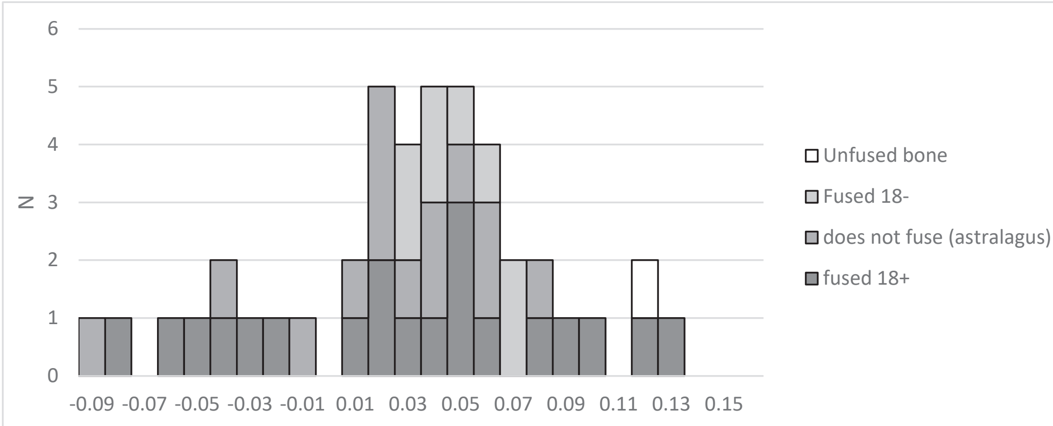

Fig. 4. The LSI of measurements of sheep of Bestansur, dark grey = fused elements which fuse after an age of 18 months (n = 20), lighter shade of grey = elements which do not fuse (only the astragalus) (n = 14), lightest shade of grey = fused elements, which fuse before an age of 18 months (n = 8), white = unfused elements (n = 1).

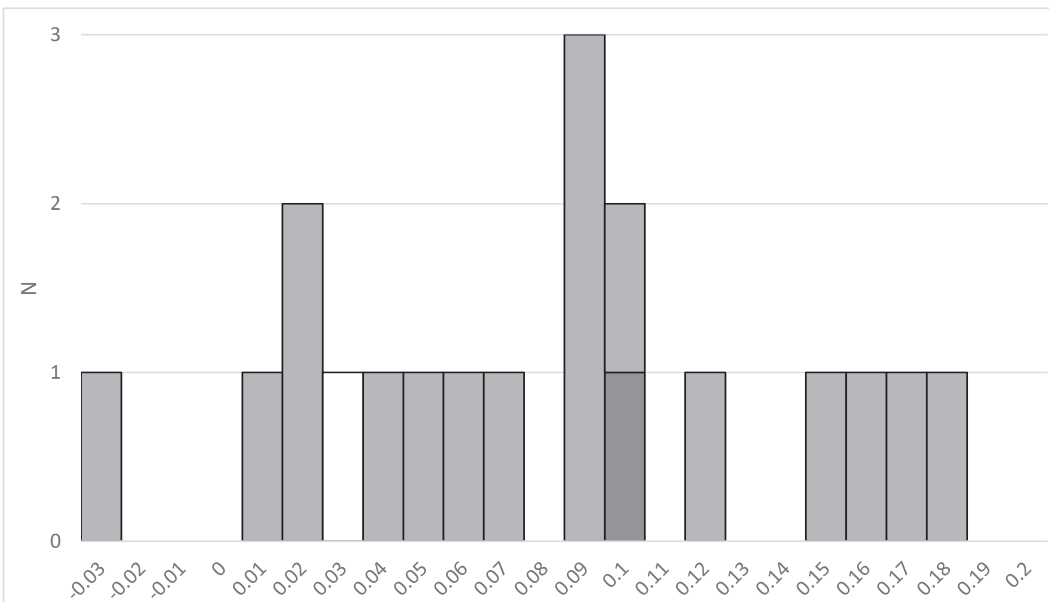

Fig. 5. The LSI of the measurements of goat of Bestansur (only breadth measurement included). dark grey = fused elements which fuse after an age of 18 months(n = 1), lighter shade of grey = fused elements, which fuse before an age of 18 months (n = 17), white = unfused elements (n = 1), see legend in Fig. 4.

4. Results

4.1. Zooarchaeological results

Caprines are the most abundant taxon at Bestansur. Most of these remains identified as sheep/goat (Fig. 3b), but as sheep outnumber goats in a ratio slightly higher than 2:1 (Fig. 3) we can infer that ca 60% of the sheep/goat bones likely represent sheep. The ratio of sheep and goats in the Neolithic Zagros Mountains is likely related to the elevation of the sites (Bendrey et al., 2020, 328); at Karim Shahir and East Chia Sabz sheep also dominate over goat (Figs. 1, 3). Jarmo, shows a different pattern from Bestansur, with goat slightly more abundant than sheep. At the Neolithic highland sites Sheikh-e Abad and Ganj Dareh goat significantly outnumber sheep (Figs. 1, 3).

4.1.1. Ageing and biometry

The sample size for age reconstruction based on bone fusion for Bestansur is modest (Table 1). The majority of sheep and goat at Bestansur reached an age into maturity (Table 1). Unfused bones are known to be more porous and suffer greater taphonomic attrition (Zeder, 2008), so are likely underrepresented. Also, they are less often identifiable as either sheep or goat (Table 1), which makes it harder to reconstruct species-specific kill-off patterns. Many of the unfused elements were not suitable for measurement, so only one unfused element of sheep and one of goat are represented in the LSI graphs (Figs. 4, 5).

At Bestansur, recorded sheep all reached maturity and mainly prime adults are represented (Table 1). The LSI data are negatively skewed and the kurtosis is positive (Skewness: −0.75, Kurtosis: 0.87) (Fig. 4), which is consistent with a focus on male prime-adults. The elements of sheep which reached an age into maturity are represented in all size categories in the LSI graph, indicating that there was no young male cull. The assemblage clearly indicates a hunted assemblage with a focus on male prime adults.

All unfused bones of goat in the assemblage belong to animals which have been slaughtered between an age of 12–18 months. Most unfused bones of the 'caprine' group also are from animals between 12 and 18 months, but the sample size is too limited to draw definite conclusions from these data. A wide distribution in the size range of goats is visible

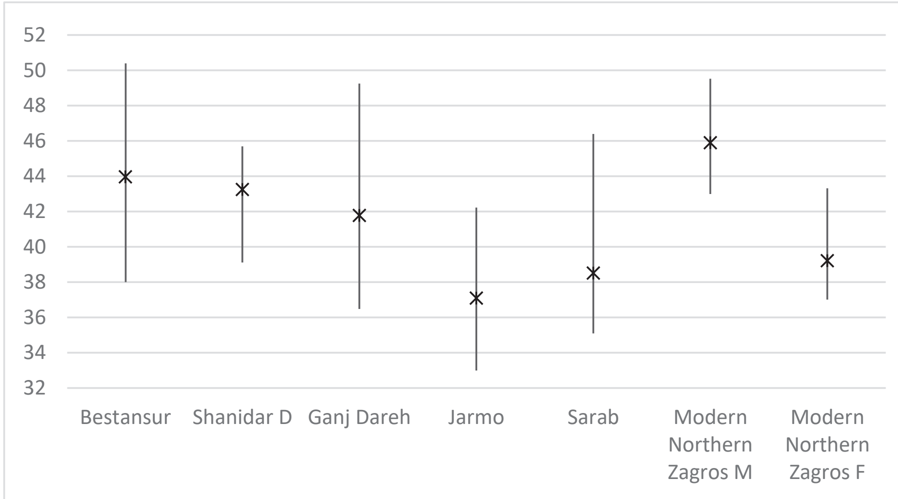

Fig. 6. Comparison at different sites of the GL of the first phalange of goat. A cross represents mean and lines end with minimum and maximum measurement from each site (only fused bones included), modern northern wild goat of the Zagros M/ F M = male F = Female, N = from left to right 9, 3, 55, 38, 29, 23, 23, data of sites for comparison from Zeder, 2008 appendix, see SI for dating).

(Fig. 5). The LSI distribution of the goat is slightly negatively skewed and the kurtosis is negative too (Skewness: −0.126, Kurtosis: −0.261). The vast majority of the bones in the graph are elements which fuse before an age of 18 months. Therefore, it is not possible to determine whether the tail at the right end (the male individuals) are indicative of young male cull. Given the modest sample size and the few unfused bones suitable for measurement, as well as bones which fuse after an age of 18 months, it is not possible to determine whether goat management at Bestansur involved culling young males.

The zooarchaeological assemblage of Ganj Dareh has been restudied by Zeder (2008). The large sample size made it possible to reconstruct sex specific harvest patterns. Biometry combined with bone fusion data indicated a focused kill-off of males between 1 and 2 years of age, while the females were kept alive for reproduction (Zeder, 2008, 249-51). The metrical data of the site indicate that the zooarchaeological assemblage is dominated by female goat, which is to be expected when young male culling is practiced, since unfused bones survive less well in the archaeological record and are less identifiable to species level (Zeder, 2008). Sheep at Ganj Dareh, however, tend to reach an age well into maturity (Zeder, 2008, 262). The biometric data show a heavy skew towards males, which is indicative for a hunted population (Zeder, 2008, 263).

At Jarmo, caprines are the most abundant animals in both the Early Neolithic as well in the Pottery Neolithic (Zeder, 2008) (Fig. 3). Since no sieving was undertaken during the excavations in the 1950 s (, there is a likely recovery bias against the recovery of unfused bones (Zeder, 2008). The majority of the zooarchaeological assemblage consists of bones from the Pottery Neolithic. At Jarmo (Early Neolithic and Pottery Neolithic levels combined), the skewness for biometric data for both sheep and goat are positive (Zeder, 2008; Arbuckle and Atici, 2013). For goat, there seems to have been a young male culling patterns since the Early Neolithic (Zeder, 2008), although this is less evident than at Ganj Dareh,

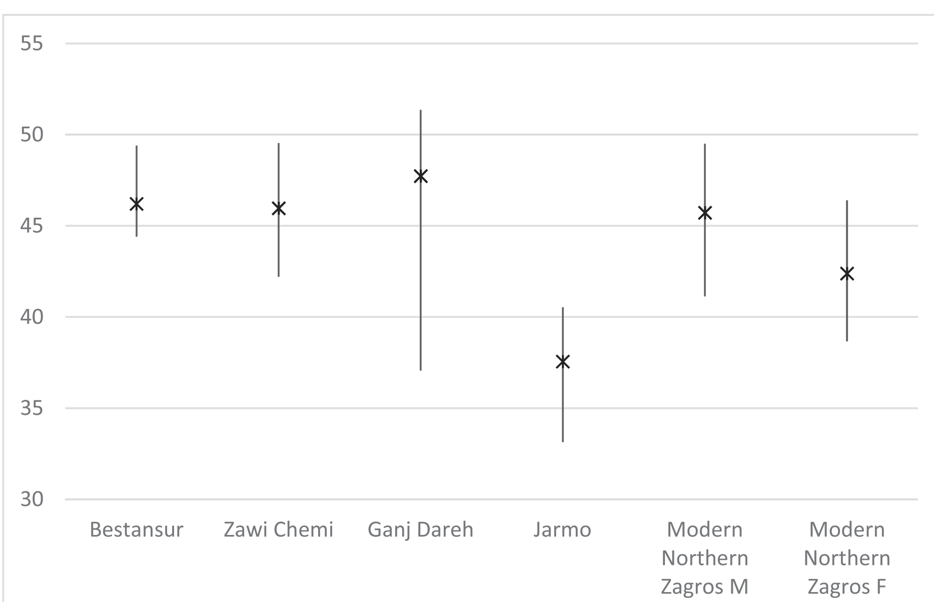

Fig. 7. Comparison at different sites of the GL of the first phalange of sheep. A cross represents mean and lines end with minimum and maximum measurement of the sites (only fused bones included). modern northern wild sheep of the Zagros M/ F M = male F = Female, N = from left to right 9, 18, 18, 10, 154, 135 data of sites for comparison from Zeder, 2008 appendix see SI for dating).

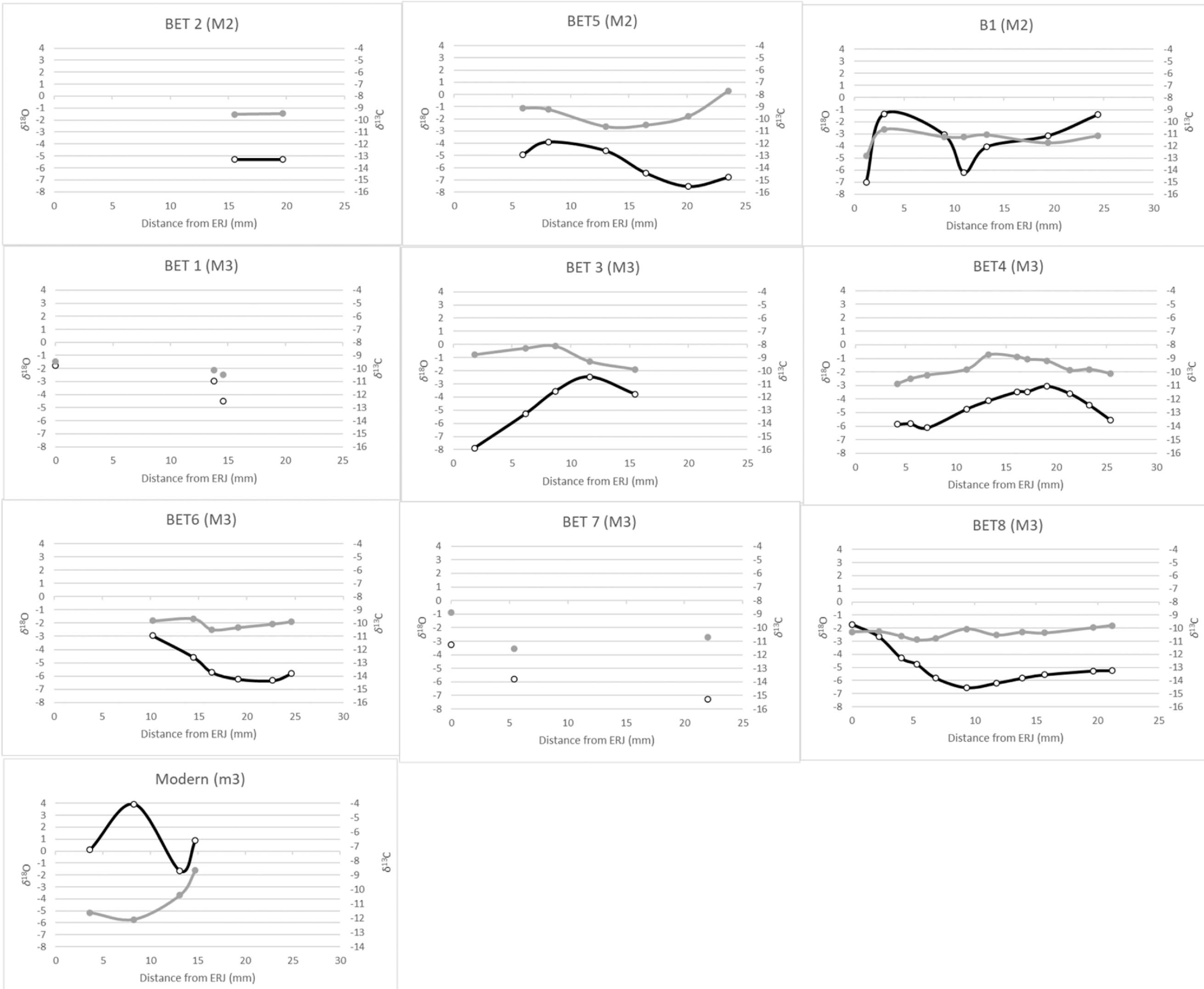

Fig. 8. Sequential carbon (grey) and oxygen (black) isotope data from Bestansur.

possibly due to the recovery bias. Goats are clearly smaller in size at Jarmo than at Bestansur and Ganj Dareh (Fig. 6). This decrease in size seems to have happened during the Pottery Neolithic, as at Sarab, another Pottery Neolithic site, goat are smaller as well (Zeder, 2008). It is unclear why there is this overall decrease in size during the Pottery Neolithic (Zeder, 2008). At Jarmo, the sheep population, however, does not seem to have been herded until the Pottery Neolithic period (Zeder, 2008). Jarmo is still one of the earliest sites in the Zagros where both domestic goats and domestic sheep are present together in the Pottery Neolithic. The skewness of the LSI is positive, suggesting a managed herd (Zeder, 2008; Arbuckle and Atici, 2013). As noted, sheep are less sexually dimorphic than goat (Fig. 7; Zeder, 2008) and the size range of the first phalanges of sheep is smaller in all populations, as is the size difference between the modern male and female specimens. In the Pottery Neolithic sheep are smaller than the preceding Early Neolithic sheep as was also seen in goat at Jarmo (Fig. 7). There is no evidence for local domestication of sheep in the Zagros region (Zeder, 2008); rather smaller-bodied domestic sheep may have been introduced from a neighbouring region.

4.2. *Isotope analysis*

4.2.1. *Bestansur*

The isotopic data of the modern sheep molar show that the lowest ^{13}C values coincide with the highest δ^{18}O values, which would be present during the winter (Fig. 8), this could indicate vertical transhumance or winter foddering. Foddering of straw and barley harvested during other seasons indeed occurs in the present-day village of Bestansur (Elliot et al., 2015) and the animals are kept close to the site during the entire year. Preservation of the archaeological teeth was modest, of 130 sequential samples in total, 60 samples from Bestansur survived the pre-treatment: the remaining 67 dissolved completely during the acid step. Since the sheep/goat ratio at Bestansur is 2:1, the molars are likely to derive from both sheep and goat. All the molars of which enough samples survived show roughly sinusoidal seasonal curves in their δ^{18}O values, except for BET8 (Fig. 8). The mean value of the δ^{18}O values is −4.7 ‰(±1.6‰,1sd), with a maximum of −1.3 ‰ and minimum of −7.9 ‰ (Fig. 11) Since the amount of samples per molar vary highly due to the pre-treatment survival, it is hard to draw comparisons between minimum and maximum values between the teeth. The maximum intra-tooth variation in δ^{18}O is 5.7 ‰ (Fig. 11) and ranges of δ^{18}O are on average smaller than at Jarmo and Ganj Dareh (no range >6‰) (see Fig. 11). Based on the δ^{18}O data obtained, Bestansur was either not

Table 2
averages, minima and maxima of the isotopic values per site.

Site	average ‰ δ^{13}C	‰ 1 s.d.,	Minimum ‰ δ^{13}C	Maximum δ^{13}C	Average ‰ δ^{18}O	‰ (1 s.d.),	Minimum ‰ δ^{18}O	Maximum ‰ δ^{18}O
Jarmo	−9.9	0.9	−12.4	−7.6	−2.3	2.2	−6.9	4.4
Ganj Dareh	−9.5	1.2	−13.7	−6.0	−1.6	2.4	−8.8	3.1
Bestansur	−10.0	0.9	−12.8	−7.7	−4.7	1.6	−7.9	−1.3

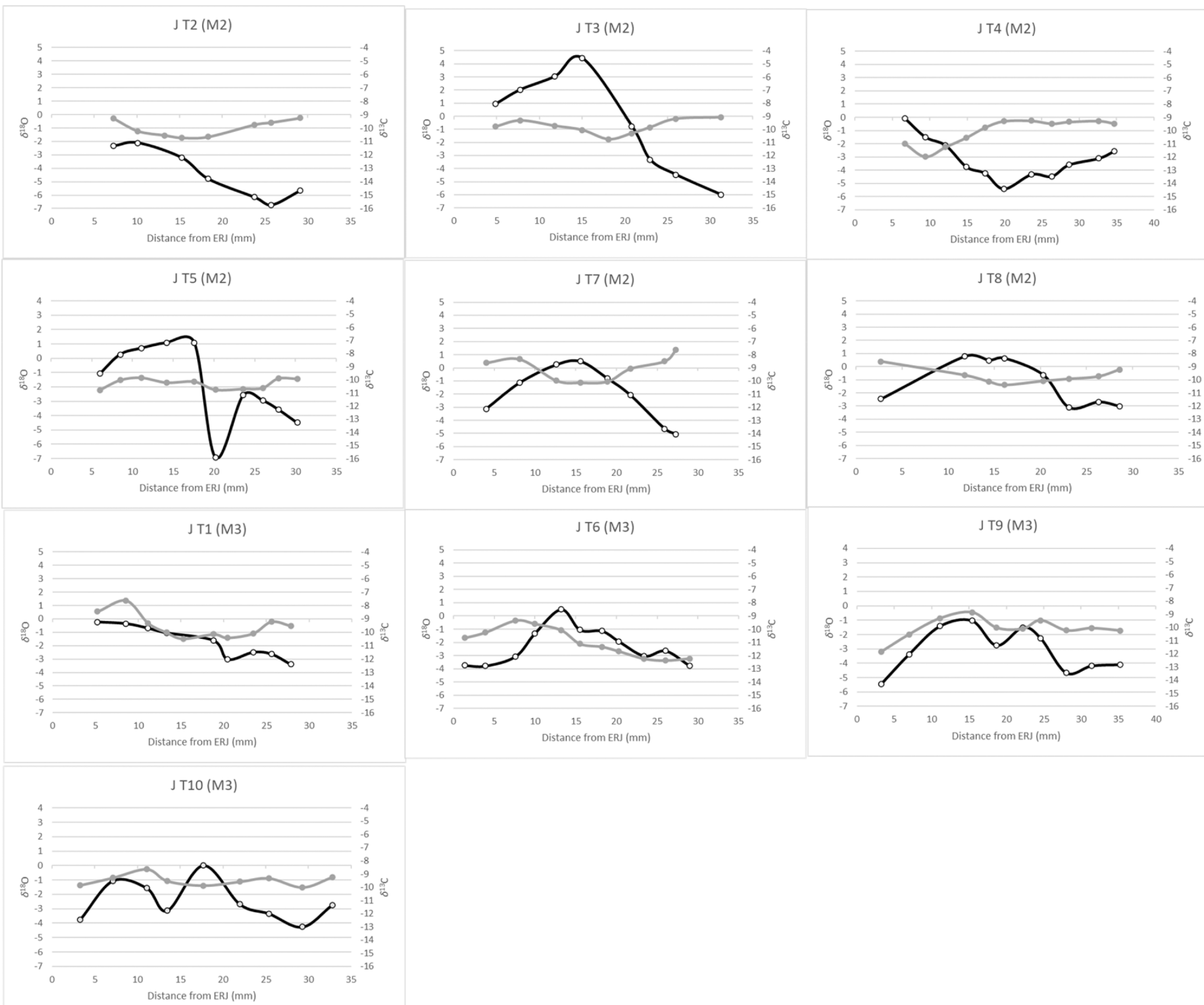

Fig. 9. Sequential carbon (grey) and oxygen (black) isotope data from Jarmo.

strongly seasonal at the time, or that animals were moved to the cooler highlands during the summer months. However, the small intra-tooth variations in δ^{18}O could be partly due to small sample size and the many incomplete sequences. The lower average of δ^{18}O values in the teeth from Bestansur compared to teeth from Jarmo and Ganj Dareh (see Fig. 11) is curious, since Bestansur is located on a lower elevation were δ^{18}O of meteoric values would expected to be higher (Table 2; Fig. 9) (Section 3.3). Bestansur is located on a karst aquifer (Elliot et al., 2015) which could have influenced the δ^{18}O values of the water ingested by the animals. It is also possible this is related to differences in diet and water intake between sheep and goat, since the majority of caprines at Bestansur are sheep and the majority at Ganj Dareh are goat (Section 3.3; 4.1). The mean of the δ^{13}C is −10.0 ‰., (0.9sd.), with a maximum of −7.7 ‰ and minimum of −12.8 ‰ (Table 2) . In the majority of the molars the maximum δ^{13}C value is close to the highest δ^{18}O value (BET 3, BET4, BET6); only in BET5 the lowest δ^{13}C coincides with the δ^{18}O values. It would be expected that the δ^{18}O peak and the δ^{13}C peak coincide if the animals were grazing in the local area or an area around the same altitude, and were not given C_3 enriched fodder during winter months, since during summer grasses get enriched in ^{13}C (see Section 3.3). The one tooth were the δ^{13}C peak coincides with the lowest δ^{18}O values could either be a managed animal which was brought to higher elevations during summers months, a wild sheep/goat which migrated or a managed animal which was foddered during winter.

4.2.2. Jarmo

The preservation of the teeth was modest and the teeth had many grooves and punctures therefore some of the samples might have been subject to diagenesis or collagen might have been drilled. Of 98 samples from 10 teeth, 94 survived the pre-treatment. The sheep/goat ratio at

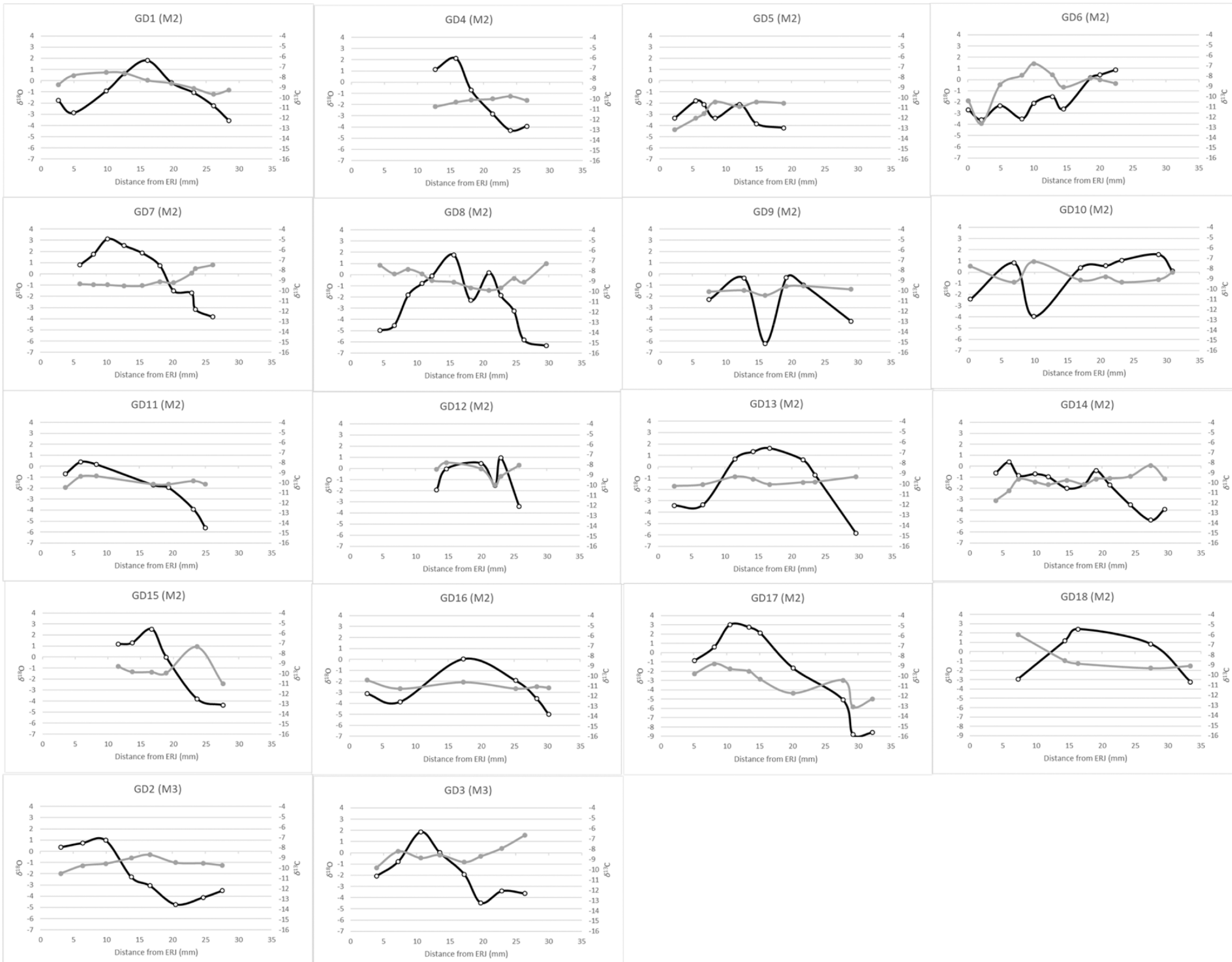

Fig. 10. Sequential carbon (grey) and oxygen (black) isotope data from Ganj Dareh.

Pottery Neolithic Jarmo is about 1:3, so the molars are likely to come from both sheep and goat. The average value of the $\delta^{18}O$ values is −2.3‰ (± ‰2.2, 1sd), with a maximum value of 4.4 ‰ of and minimum value of −6.9 ‰ (Table 2; Fig. 9, 11). Eight molars show sinusoidal seasonal curves, while one M_2 (JT4) and one M_3 (JT1) do not. The max intra-tooth difference in $\delta^{18}O$ values is 7.6 ‰ (Fig. 8, 10). Two of the molars with sufficient samples to cover an annual cycle (JT3, JT5) show a range of >6‰ and therefore indicate strong seasonality (Henton, 2012) (Fig. 9, 11).

The mean of the $\delta^{13}C$ values is −9.9 ‰ (±0.9‰, 1sd), w with a maximum of −7.6 ‰ and minimum of −12 ‰, which is very similar to Bestansur. However, a very different relationship between the oxygen and carbon isotopic values can be observed. In the $M_{2,}$ JT4, JT3, JT7, JT8 the highest $\delta^{13}C$ values are coinciding with low $\delta^{18}O$ values, while in JT2 and JT5 the two highest $\delta^{13}C$ values are coinciding with both the lowest and highest $\delta^{18}O$ values (Fig. 9). In the M_3′s this pattern in less evident, but in JT6 the highest $\delta^{13}C$ value precedes the peak values in $\delta^{18}O$. This pattern could indicate that the sheep and goat were brought to higher altitudes during the summer or given $\delta^{13}C$-enriched fodder during the winter. Since in JT2 and JT5 high $\delta^{13}C$ values are present both during the supposed winter and summer months, but not during autumn and spring, it could mean that the caprines were kept around the site for most of the year and given ^{13}C enriched fodder during the winter.

4.2.3. Ganj Dareh

18 M of Ganj Dareh were sampled, in total of 185 samples, 146 samples (of 18 teeth) survived the pre-treatment. Unlike at Jarmo and Bestansur, most of the molars are likely to derive from goat, since they make up 94 % of the caprines. The average value of the $\delta^{18}O$ values is −1.6 ‰ (±2.4‰, 1sd) with a maximum value of 3.1 ‰ and a minimum value of −8.8 ‰ (Table 2) . The $\delta^{18}O$ values of 15 of the 18 M show sinusoidal curves. The maximum intra-tooth difference in $\delta^{18}O$ values is 11.8 ‰ (Table 2; Fig. 10, 11). Twelve of the Ganj Dareh teeth have $\delta^{18}O$ ranges > 6 ‰ indicating strong seasonality. The mean of the $\delta^{13}C$ values is −9.5‰ (1.2 ‰s.d.), between a maximum of −5.3 ‰ and minimum of −13.7 ‰ (Table 2). While the average $\delta^{13}C$ value of the samples of Ganj Dareh is similar to Bestansur and Jarmo, the total range of the $\delta^{13}C$ values is wider than at either site (7.7‰ vs 5.1‰ (Bestansur) and 4.8‰ (Jarmo)). Also, the higher $\delta^{13}C$ values intra-tooth do not coincide with the higher $\delta^{18}O$ values (Table 2, Figs. 10, 11). These higher $\delta^{13}C$ values could indicate movement of the animals to a higher elevation during summer or as winter foddering. In contrast to Bestansur and Jarmo, Ganj Dareh is located in the high Zagros. Since it is likely that environments at higher elevations the environment would be more depleted in $\delta^{13}C$ than in the environments at Jarmo and Bestansur, it is possible winter fodder enriched in $\delta^{13}C$ relative to local fauna, was foddered to the animals. It is also possible vertical transhumance was practiced. Although this seems less likely since the intra-tooth $\delta^{18}O$ values indicate large seasonal differences (Fig. 11), and if vertical transhumance was practiced, it would be expected that there lesser degree of variation in $\delta^{18}O$ values, since $\delta^{18}O$ is positively correlated with temperature and negatively correlated with altitude (see Section 3.3).

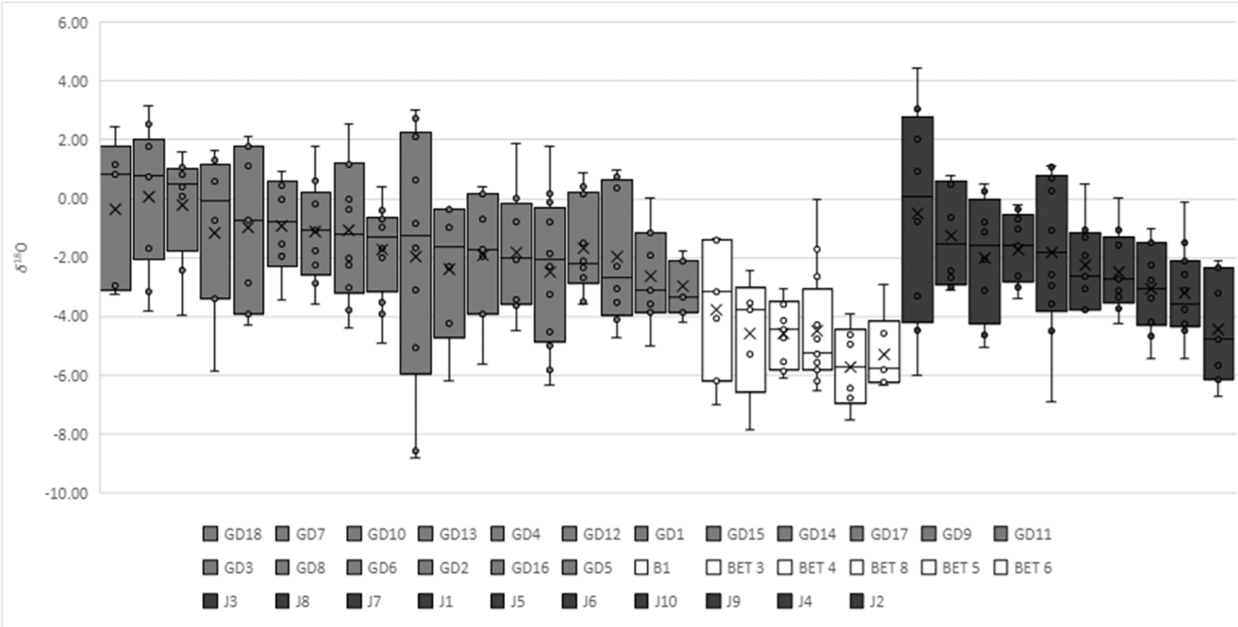

Fig. 11. Boxplot of the $\delta^{18}O$ values (all sequences with >5 datapoints included, in order of descending mean value), light grey = Ganj Dareh, white = Bestansur, dark grey = Jarmo.

The isotopic values from Bestansur indicate that animals of which teeth were sampled were possible living close to the site and not moving over significant altitudes. However the sample size is small, so it is hard to draw definite conclusions about possible management practices on the entire population. The isotopic values from Ganj Dareh and Jarmo both indicate that either the animals were taken to higher altitudes over summer or foddered during winter. When comparing the different sites it is important to acknowledge dietary differences of sheep and goat, the intra-site differences and differences between sites in isotopic values could be partly due to the species difference. Since sample size is limited, it is hard to draw further conclusions how much impact sheep/goat differences have on the overall isotopic outcomes. At Pottery Neolithic Jarmo both sheep and goat were likely to be managed by humans, but humans could have applied different management strategies on sheep goat. This cannot be further inferred from the current dataset.

5. Discussion and suggestions for further research

Caprines are the most abundant animal group at Bestansur, Jarmo and Ganj Dareh, so they were certainly of significant dietary value at all three sites. Evidence indicates that goats were closely managed at Ganj Dareh. The kill off patterns show strong evidence for young male cull (Zeder, 2008). The isotopic data indicates that either the animals were moved over summer or foddered during winter. Since Ganj Dareh is located in the high Zagros, moving animals to even higher elevations during summer seems unlikely and the $\delta^{18}O$ values suggest strong seasonality. The goat were possibly kept close to the sites, and possible been given ^{13}C enriched fodder during the winter. The presence of goat on site at Ganj Dareh is supported by analysis that showed the presence of foetal goat bones and shed deciduous teeth, as well as penning deposits and high concentrations of dung spherulites on site (Yeomans et al., 2021). Evidence for goat management is supported by recent aDNA analysis of goat, which shows genomes in two distinct clusters: those with domestic affinity and a minority group with stronger wild affinity, indicating that managed goats were genetically distinct from wild goats at Ganj Dareh. However, no genomes related to morphological change observed in domesticated goat in later periods were present at Ganj Dareh (Daly et al., 2021). At the lowland site of Bestansur, sheep were more abundant than goat, but based on the kill-off pattern there is no evidence that sheep were managed. Instead, wild sheep would have made a larger contribution to the diet at Bestansur than possibly managed goat. Due to the modest sample size, it is difficult to determine whether there was a young male goat cull at Bestansur. Herbivore faecal material was found in occupational areas (Elliott, 2020), as well as the shed milk tooth of a goat (Bendrey et al., 2020, 321), indicating that managed animals might have been present on the site. Furthermore, micromorphological analysis at Bestansur indicates that dung was used as a source of fuel (Elliott, 2020). Dung types found in oven areas derived from herbivores (Elliott, 2020, 391), so dung might have been an important resource from caprines too. Isotopic analysis did not indicate that people foddered animals during winter or moved them over vertical distances. At Jarmo, the young male cull management pattern in goat is less evident than at Ganj Dareh but still visible, which might be due to recovery bias against unfused bones (Figs. 3, 5; Table 1). The isotopic values of the sampled teeth from Pottery Neolithic Jarmo indicate possible transhumance was practiced, or that the animals were foddered during winter. Further research could include ZooMS to distinguish isotopic signals of sheep and goat (Pilaar Birch et al., 2019), since it is impossible to determine at the moment what differences in isotopic values are related to species difference. This could indicate which differences in isotopic values are related to differences in the diet of sheep and goat, and being able to isolate these results, it would be possible to identify transhumance and winter foddering through isotopic analysis with greater accuracy.

Declaration of Competing Interest

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

Data availability

data are in the supplementary information.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.103936.

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