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Sheep and Goat Variability along the Edges of the Al-Hajar Mountains in the Prehistory of South-east Arabia

RESEARCH PAPER

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ABSTRACT

The Al-Hajar Mountains, spanning the Sultanate of Oman and the United Arab Emirates along the Sea of Oman, have hosted human settlement since prehistory. Over the past three decades, numerous archaeological sites have been investigated in this region. Findings from these sites reveal significant human impact on the landscape from the Early Bronze Age to the Late Iron Age, evidenced by complex settlements and extensive burial grounds. This study synthesizes recent zooarchaeological data and presents the first exploratory osteometric analysis of sheep and goats from southeastern Arabia, the most abundant and extensively exploited terrestrial mammals in the region's prehistoric record. By examining metrical data from key archaeological sites, this paper assesses size variation patterns in these species through statistical evaluation. The study primarily focuses on documenting differences in bone size and shape, but also provides a foundation for future studies aimed at understanding broader aspects of animal management, environmental adaptation, and socio-economic dynamics among both inland communities along the Al-Hajar Mountains and fisherfolk on the Arabian Sea coast.

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INTRODUCTION: ZOOARCHAEOLOGICAL FRAMEWORK AND SITES OVERVIEW

In recent decades, a series of zooarchaeological investigations have been conducted on the faunal remains from archaeological sites in the Sultanate of Oman, including the Musandam Peninsula, and in the eastern United Arab Emirates, shown in Figure 1 and listed in Table 1. This study represents the first publication of metrical data from these investigations, which until now had only been addressed in separate studies and remained unpublished. For this reason, the present contribution aims to bring together and summarize recent zooarchaeological data, namely faunal spectra and osteometric measurements, from southeastern Arabia, and develop a first exploratory osteometric investigation focused on postcranial bones' measurements of sheep and goats. This study aims to assess morphological variability and provide a preliminary dataset for future comparative analyses.

The zooarchaeological analyses conducted so far have made it possible to observe that the subsistence strategy relied, everywhere and in all periods, upon the exploitation of local animals (Genchi et al. 2018; Maini & Loreto 2022; Power et al. 2024; Strolin & Studer 2018). The subsistence economy of Neolithic and Early Bronze Age coastal settlements, e.g. the settlements located in the Ras Al-Jinz bay or the Ras Al-Hadd area,[1] mainly focused on marine resources, with evidence of differentiated fishing of pelagic and coastal species, including dolphins and turtles, integrated with the harvesting of mollusks, while land mammals (both domestic and wild) are always extremely scarce (Martin 2002; Mosseri-Marlio 2002; Borgi & Maini 2020; De Rorre et al. 2020). Conversely, during both of the main occupational phases at the Salut territorial compound, land mammals, mainly domesticated, are the most exploited resources, while marine sources, due to the long distance from the sea, are rare (Strolin & Studer 2018).

Despite local variations, the collected data show that caprines are the most frequently encountered and economically significant terrestrial mammals in the region's prehistoric faunal record.

For the metrical approach, the Logarithmic Size Index method (LSI) is applied to sheep and goat long bones. For the statistical approach, Kruskal-Wallis and Dunn's tests are performed for pairwise comparisons between sites and periods. In addition, a focus on the metrics of astragali (knucklebones) is presented using the method for sheep/goat discrimination published by Davis (2017).

ARCHAEOLOGICAL BACKGROUND

All sites are located in the flat, inland or coastal areas near the foot of the Al-Hajar Mountains that run in a north-west/south-east direction along South-East Arabia (Figure 1).

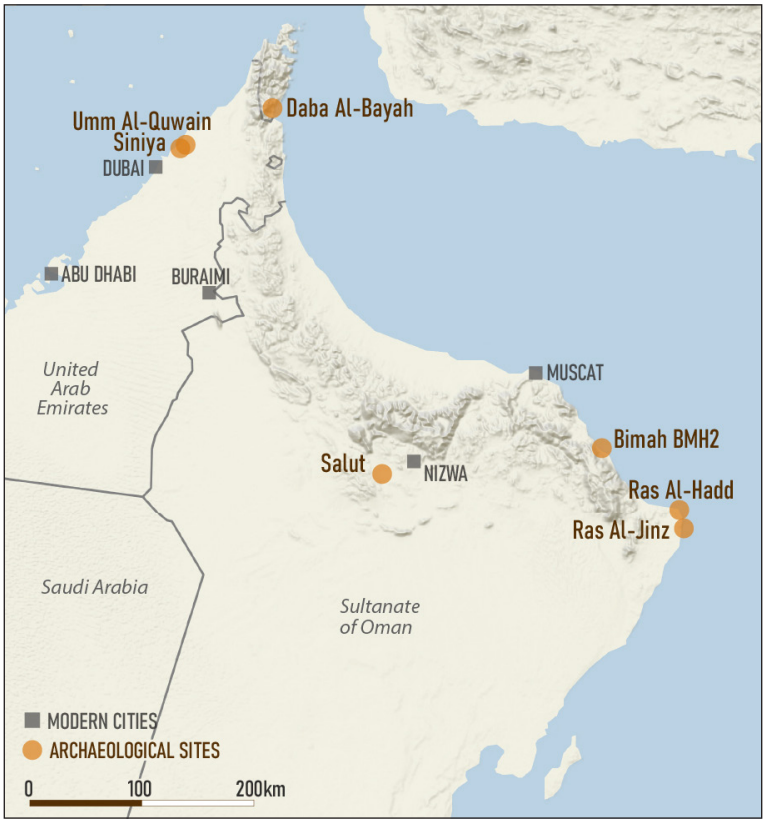

Figure 1 Map of the sites cited in the study.

The first site in the study is the wide settlement of **Salut at Bisya**. Salut is composed of a fortified site (*Husn* Salut) with adjacent settlement (*Qaryat* Salut) and a multi-phase Tower (ST1). The occupational area was located in the Al-Dakhiliyah region of inland Oman and was excavated by the IMTO Archeological Mission.[2] The large settlement of Salut is located at the piedmont of the Al-Hajar mountains near the junction of two wadis that made the area a preferential spot for human settlement. The surrounding plain and the rocky slope were covered by shrubby vegetation, typical of sub-desertic areas, as confirmed by archaeobotanical studies (Bellini et al. 2011).

Salut Tower 1 (ST1), dated to the Early Bronze Age, includes a complex hydraulic system with a well and a series of channels for water management and storage structures, sustaining both people and agriculture (Degli Esposti 2016). Faunal remains from ST1 revealed that animal economy mainly relied on domestic ruminants. Goat (*Capra hircus*) in particular, with a smaller percentage of sheep (*Ovis aries*), represent the majority of finds (80% of the remains). Cattle (*Bos taurus*) is also present but is less frequent (Strolin 2018). As for caprines, age-at-death data based on molar wear stages (after Grant 1982) indicate that most remains belong to adults older than 1–2 years and sex data based on coxal bones and horn cores indicate a predominance of females, with a male-to-female ratio of 1:3.5. The study thus suggests an exploitation of small stock both for primary and secondary products. In addition to zooarchaeological data, lipid residue analyses of pottery sherds from ST1 confirmed this scenario as ruminant adipose fat residues as well as milk residues were detected (Suryanarayan et al. 2024).

The Early Iron Age occupation of Salut includes a fortified outcrop (*Husn* Salut) where ceremonial activities took place and a settlement in the surrounding plain (*Qaryat* Salut). The modifications observed over time in the ditch system of ST1 reflect the human response to the climatic aridification that occurred between Bronze and Iron Age (Degli Esposti 2011; Degli Esposti 2016; Fleitmann et al. 2007). Moreover, water-management systems typical of the region, collecting water from piedmont aquifers, are documented in the Iron Age and made the site self-sufficient as some agriculture was practiced in the surrounding plain (Cremaschi et al. 2018; Degli Esposti et al. 2018).

Excavations at Early Iron Age Salut resulted in a significant quantity of animal remains indicative of animal husbandry with exploitation of primary and secondary products. Domestic species, in particular caprines, are predominant (92.5% of the faunal assemblage) with goats outnumbering sheep, together with a scarce presence of cattle. The mortality profile for caprines, based on mandibular wear stages, shows how adult animals over three years of age were preferentially exploited. The sex ratios based on coxal bones and horn cores demonstrate a clearly higher frequency of females (male-to-female ratio being 1:9) for the goats. This suggests goat herding mainly aimed at secondary products—milk, hair, skin—and reproduction. While sheep herding was probably less focused on milk and more on meat as well as on wool (Strolin & Studer 2018).

The second site that has yielded considerable quantities of faunal remains is the funerary structure **LCG-2 at Daba Al-Bayah**, located in the Musandam Peninsula of northern Oman, and excavated by the MASPAG Project.[3] The funerary complex of Daba Al-Bayah, located in the eastern part of the Musandam Peninsula, is composed of several graves. The Large Collective Grave 2 (LCG2), constructed during Iron Age II and continuously used until the Pre-Islamic Recent period, is a corridor-shaped structure, about 24 meters long and 4 meters wide, containing hundreds of individuals accompanied by thousands of valuable artifacts (Genchi, Ramazzotti & Larosa 2022). Approximately 2800 animal bones have been found in this collective grave, mainly in close association with human skeletons. More than 90% of these bones are identified as land mammals, with caprids being the most represented species. Goats are ten times more frequent than sheep, while cattle, dogs, and equids are very rare. Camels and pigs are only represented by a few fragments. LCG2 exhibits multiple types of human depositions. The most recent phase is characterized by secondary or greatly reduced burials organized in different clusters, resulting from anthropogenic actions to accommodate new burials over time. In a second phase, circular burial chambers were constructed along the perimeter walls, in addition to the main stone structure. As excavations progressed, the discovery of primary depositions increased, and a clear association between humans and animals became evident (Genchi et al. 2018; Genchi, Ramazzotti & Larosa 2022). Inside the central corridor, designed to host several burials along the mobility corridor located in the middle, more than 40 primary depositions were discovered. These are often accompanied by a wide range of grave goods, including stone, pottery and metal vessels, metal objects, ornaments, ritual tools, as well as animal remains, especially goats. Typological analysis and ^{14}C dating place this coherent group of burials in the second half of the 1st millennium BC, during the Iron Age III (600–300 BC). At least 20 of these depositions, located inside burial chambers or at the base of the main walls, show a close relationship between humans and animals suggesting complex rituals and significant attention to details in the preparation of the burials and in the choice of the grave goods. Entire or partial carcasses of caprines are arranged in partial anatomical connection behind the head or at the feet of the human bodies. These animal skeletons, all belonging to adult individuals, have contributed to our understanding of cultic practices and the *chaîne opératoire* of carcass processing; they have also increased the number of available bone measurements.

Finally, the site of **Bimah BMH2** is included in the analysis. BMH2, excavated by the University of Naples "L'Orientale", is located in Ash-Sharqiyyah North region and is the only Early Iron Age site (900–600 BC) located directly on the seashore in this part of Oman.[4] Bimah BMH2, a small seasonal settlement dated to the final phase of the Early Iron Age, occupied a strategic location facilitating direct connections between inland regions, such as Lizq, and the coast (Loreto 2018). Excavations revealed significant quantities of animal bones, along with pottery, stone vessels, shell ornaments, and tools, recovered from different layers of the main residential and functional compounds. These areas featured fireplaces and spaces for food processing and consumption, indicating a well-structured subsistence economy. Fish was the primary exploited resource, but terrestrial mammals are much more abundant compared to what emerges from the faunal spectra of Bronze Age coastal sites.[5] Small domestic ungulates such as sheep and goats dominate the faunal assemblage, followed by cattle and the occasional presence of dogs (*Canis familiaris*); equids and camels are notably absent. Wild game is represented exclusively by gazelles (*Gazella* sp.). Age-at-death analysis indicates that sheep and goats were also exploited during the reproductive season, as evidenced by the remains of very young individuals slaughtered within their first months of life or immediately after weaning. This suggests that the settlement was occupied by herders and their flocks during the late winter and early spring, coinciding with the birth season. Livestock management at Bimah likely played a crucial role in the local subsistence economy, possibly linked to the irrigated agricultural areas in the interior, accessible via nearby wadis (Maini & Loreto 2022).

In the UAE, zooarchaeological evidence from **Umm Al-Quwain** is considered in this study and includes the Iron Age occupation at the site of Tell Abraq, excavated by the IAMUQ Archeological team,[6] along with structures belonging to different chronological phases recently discovered on Siniya Island, excavated by the SIAP Project[7] (Table 1).

In late 2019, stratigraphic excavations were resumed in the eastern area of **Tell Abraq**, a multi-period site located at the border between the territories of Umm Al-Quwain and Sharjah Emirates. Tell Abraq is notable for its continuous human occupation from circa 2500 BC to AD 300. The current research project focuses on the span between the Late Bronze Age/Iron Age I transition and the late pre-Islamic period. Recent excavations have uncovered crucial architectural features and assemblages of archaeological materials across different site phases. Work has primarily focused on three areas where nine trenches were excavated. Among these, in Trenches 2 and 3, a large section of the site's massive surrounding wall and an associated ancient ditch were uncovered. In Trench 4, excavation of a large building, referred to as "the palace," revealed new walls and evidence of structural changes due to possible destruction events. The material culture from the site indicates a continuous occupation throughout the 1st millennium BC and the early centuries AD. The palace is a unique discovery in South-East Arabia, dating back to the transition from the 2nd to the 1st millennium (Degli Esposti et al. 2023).

Zooarchaeological analyses of the numerous faunal remains from Tell Abraq are ongoing, in parallel with the excavation campaigns. The current research focuses on the Iron Age phases, mainly Iron Age II. Hence, only a preliminary overview can be presented. The animal remains exhibit a varied faunal composition. Marine resources constitute the primary assemblage, accounting for 60% of the protein exploited at the site. However, land mammals are also present and significant, making up 30% of the total animal remains discovered at Tell Abraq. Among the land mammals, small ungulates represent 90%, with caprines being the prominent group and goats three times more frequent than sheep. Protein procurement was also supplemented by the exploitation of birds, mainly cormorants (*Phalacrocorax* sp.), which were consumed at different growth stages. This indicates well-developed hunting strategies targeting lagoon resources, where the nesting areas of this species are still located today (Tomé 2003).

SITE	COUNTRY – REGION	PERIOD	CHRONOLOGY	BIBLIOGRAPHY
Salut Tower 1 (ST1)	Oman – Al-Dakhiliyah	Early Bronze Age	2400–2000 BC (Umm an-Nar)	Degli Esposti 2016
Daba Al-Bayah – LCG2	Oman – Musandam	Iron Age 2 – PIR	1000 BC-400 AD	Genchi et al. 2022
Salut Fortified area (*Husn*) & Settlement (*Qaryat*)	Oman – Al-Dakhiliyah	Early Iron Age	1300–600 BC	Avanzini, Degli Esposti 2018; Degli Esposti 2021
Bimah – BMH2	Oman – Ash-Sharqiyyah North	Early Iron Age	900–600 BC	Loreto 2018
Tell Abraq	UAE – Umm Al-Quwain	Early Iron Age (Iron Age 2)	1300–300 BC	Degli Esposti et al. 2023
Siniya LAS	UAE – Umm Al-Quwain	Late Antique	5th–6th century AD	Power et al. 2023; 2024
Siniya Old Town	UAE – Umm Al-Quwain	Late Modern Era	18th century AD	Power et al. 2023; 2024

Table 1 List of the sites considered.

Recent excavations in **Siniya Island** uncovered a Christian monastery from the 7th and 8th centuries AD, associated with a settlement. This 10-hectare settlement (Siniya LAS) contains dense mounding with building materials, pottery, glass, and shells. The excavations revealed large courtyard buildings surrounded by small double-roomed structures, probable dwellings of merchants and fishermen. Evidence of a pearling economy includes oyster-shell middens, several pearls, and a pearl diver's weight, the earliest well-dated example found in the Emirates (Power et al. 2024).[8] As expected, marine resources, in particular fish,[9] provided the majority of the protein intake of the inhabitants of the island in all the chronological periods but land mammals and birds (both domestic and wild) were exploited as well. Regarding land mammals, the most represented groups are caprines, mainly sheep but also goats. Caprines show a different type of exploitation according to the age-at-death estimates. In fact, they can be involved in milk and/or meat production following different killing strategies depending on species. Concerning food resources, a few remains of a juvenile pig (*Sus domesticus*) were also found at the settlement, while from the church in the core complex of the monastery area, two remains of dromedary (*Camelus dromedarius*) with cut marks testify to the exploitation of this animal not only as a beast of burden but also as a food resource. Moreover, the dromedary represents the only large-size ungulate documented on the Island. No bovine or equid bones, neither horses nor donkeys, were found. Finally, among the domestic animals, an entire skeleton of a dog was found inside the Monastery complex. Wild mammals are not recorded in the faunal assemblages of the Island. The only game animals discovered are turtles, dolphins—perhaps not related to hunting practices—and birds of different sizes. The birds, especially the cormorants, were surely caught and exploited on the island.[10]

METHODS

Sheep/goat discrimination was based on morphological and metrical criteria published in specialised literature (Boessneck, Müller & Teichert 1964; Payne 1969; Fernandez 2001; Zeder & Lapham 2010) and on direct comparison with local modern specimens.

Bone measurements were made by two of the authors (EM and LS) with vernier calipers with an accuracy of 0.1 mm following Driesch (1976) standards. A relevant set of biometric data on postcranial bones of sheep (81 specimens), goats (228 specimens), and several elements belonging to sheep/goat category (40 specimens) are made available and analysed in this paper. These measurements refer to the following anatomical elements: humerus (25 specimens), radius (24 specimens), metacarpus (40 specimens), femur (39 specimens), tibia (90 specimens), astragalus (76 specimens), calcaneum (22 specimens) and metatarsus (33 specimens) (see Supplementary file S1).

DIMENSION	MEASURES	ELEMENTS
Length	GL	radius, metacarpus, metatarsus, tibia, calcaneum
	GLl; Glm	astragalus
Width	Bp	humerus, radius, metacarpus, femur, tibia, metatarsus
	BFp	radius
	Bd	humerus, radius, metacarpus, femur, tibia, metatarsus, astragalus
	BFd	radius
	BT	humerus
Depth	Dd	tibia
	DD	metacarpus
	Dp	humerus, radius, metacarpus, metatarsus
	Dl	astragalus

Table 2 Post-cranial bone measurements used in the LSI analysis after von den Driesch (1976).

To improve the reliability of comparisons between phases and sites, only fused and osteologically mature bones were included, excluding bones more affected by post-fusion growth (e.g. scapula measurements and measurements derived from proximal radii and metapodials with missing or unfused distal ends, see Table 2) (Davis 2000; Popkin et al. 2012).

Moreover, any bone with surface damage, alterations or pathologies that could interfere with comparisons was excluded from the study. To enhance the reliability of the analysis, skeletal elements classified solely as sheep/goat, due to their morphological ambiguity, were excluded from the statistical evaluation. The analysis on sheep and goat bones was conducted by considering the taxa both separately and collectively (see Tables 3–4).

All the analyses were performed in R (v. 2024.04.1 + 748) (R core Team 2022).

Sheep and goat sizes were investigated using a widely used zooarchaeological methodology: the Log Size Index (LSI) method (Simpson 1960; Meadow 1999; Albarella 2002; Wolfhagen 2020).

The LSI (Log Size Index) normalizes individual measurements by dividing them by a standard value and converting the result into a decimal logarithm. This approach allows measurements from various skeletal elements to be represented on a unified scale, thereby expanding the dataset. LSI values were calculated by applying the following formula:

$$LSI = log10\,x - log10\,x_{ref} = log10(x/x_{ref})$$

The LSI analysis (see Supplementary file S1) was conducted using the 'zoolog' package (Pozo et al. 2023). The standard values employed here are the measurements of sheep and goats published by Clutton-Brock et al. (1990). Length, width, and depth measurements were condensed into three respective categories using the function "*condenselog*"; in addition, the function "*priority*" was used in order to consider only one measurement per specimen (see Trentacoste, Nieto-Espinet & Valenzuela-Lamas 2018).

The robustness of skeletal elements has been used as a proxy for understanding changes in animal size. For instance, increased robustness may reflect selective pressures such as adaptation to arid environments, as broader bones are associated with greater load-bearing capacity. Conversely, reduced robustness may indicate smaller, more gracile animals, potentially due to limited resources or selective breeding practices emphasizing other traits.

In addition, other factors influencing body size and proportions, such as genetics, nutrition, climatic conditions, and management practices (e.g., castration or sex ratios), were acknowledged as potential contributors to the observed variability (Davis 1996; Davis 2000; Popkin et al. 2012). These variables were factored into the interpretation of the results, although their precise influence remains beyond the scope of this study.

Kruskal-Wallis and Dunn's tests for pairwise multiple comparisons were used to assess and compare statistical differences in LSI values between sites and phases, as most of the samples had a non-parametric distribution. Additionally, effect size as η^2 was calculated for each p-value that was statistically significant in K-W test (Tomczak & Tomczak 2014). The interpretation of the magnitude of the effect size is based on Cohen's f-index (1992: 157, Table 1, test n. 7), as for each η^2 value the relative *f-index* was calculated according to the formula given by Cohen (1992: 284 formula 8.2.22). The package 'rstatix' (Kassambara 2021) was used for statistical analysis.

Furthermore, a focus is developed on astragali (knucklebones). The discrimination between sheep and goat astragali following the methodology proposed by Davis (2017) was used. This method allows to explore the differences in the shape of goat and sheep astragali on a metrical basis through the ratios of distal breadth to lateral depth and lateral depth to greatest length (Bd/Dl, Dl/GLl Driesch *sensu*). This method was developed to metrically distinguish between populations of sheep and goats from different geographical regions and was also proved efficient to this aim by Salvagno and Albarella (2017). In the present contribution, it is applied to assess previous determinations made on morphological basis and to provide a first morphometrical overview on astragalar shape in South-East Arabia. The archaeological astragali included herein were indeed previously determined as sheep or goat based on morphological features following focused literature (Boessneck, Müller & Teichert 1964; Fernandez 2001; Zeder & Lapham 2010) and using modern comparative specimens; astragali that were assigned in the broader category of 'sheep/goat' were excluded from the analysis, so that 46 goat astragali and 19 sheep astragali could be included (see Supplementary file S2). This analysis was only performed on fully ossified sheep and goat astragali from Daba and the Iron Age phase of Salut for the Oman region and from Old Umm Al-Quwain, Siniya and Tell Abraq for UEA region. The Bronze Age phase of Salut and the site of Bimah were excluded from the analysis because of the low number of specimens (a single talus for each site). Data from modern specimens of two sheep and four goats measured by one of the authors (EM) at the zooarchaeological collection of the Institute for Archaeological Sciences, Eberhard Karls University of Tübingen were used as a reference for building the scatterplot.

All the graphics presented in this work were created with 'ggplot2' package (Wickham 2016).

RESULTS

Given the limited number of sites and the small dataset available, the results here presented are insufficient for a comprehensive spatial or chronological synthesis. Consequently, these results should be regarded as an exploratory analysis.

The raw measures and LSI data that are used in the present study are listed in Supplementary file S1.

The results of the Kruskal-Wallis test are presented in Table 3. Considering each one of the three dimensions (length, width, and depth) in sheep/goat data considered altogether for all sites, significant statistical differences are observed among sites and phases. However, the effect size of these differences is small. This means that despite the observed differences not being due to chance, they are of a reduced scale.

When analysing the data for each species separately, one can observe that goats continue to exhibit statistically significant differences in both length and width, while sheep show significant differences only in relation to width. For both species, no notable differences are observed in depth.

Pairwise comparisons were carried out using Dunn's post-hoc test. The statistically significant results are presented Table 4. Data of sheep and goat considered altogether revealed that major differences are given by the Iron Age phase of Salut: at this site, the sheep and goats seem to be less tall and robust than those from the Bronze Age phase of the same site and also than those from Iron Age Daba (see Table 4). Moreover, for these two contexts (Daba and Salut Bronze Age) no statistically significant differences were found. Considering only

TAXA	VARIABLE	n.obs	CHI-SQUARED	Df	p-value	η^2	f	MAGNITUDE
S + G	Width	267	18,592	2	<0.005	0,048	0,230	small
S + G	Length	130	12,318	2	<0.005	0,0411	0,211	small
S + G	Depth	119	4,164	2	0,007	0,2241	0,153	small
G	Width	196	12,090	2	<0.005	0,0448	0,222	small
G	Length	98	16,411	2	<0.005	0,0641	0,270	moderate
G	Depth	93	2,974	2	ns			
S	Width	71	10,895	2	<0.005	0,114	0,381	moderate
S	Length	32	0,025	1	ns			
S	Depth	26	3,490	2	ns			

Table 3 Results of the Kruskal-Wallis test for the LSI width, length and depth values among sites. In taxa S = sheep; G = goat; ns = not significant.

TAXA	VARIABLE	SITE COMPARISON	z	*p-value*
S + G	Width	Daba~Salut Iron	−2,914	0,0107
	Width	Salut Bronze~Salut Iron	−3,2812	0,0031
	Length	Daba~Salut Iron	−3,5958	0,001
	Depth	Salut Bronze~Salut Iron	−2,4034	0,0487
G	Width	Daba~Salut Iron	−3,353	0,0024
	Length	Daba~Salut Iron	−3,4488	0,0017
	Length	Salut Bronze~Salut Iron	−2,7177	0,0197
S	Width	Daba~Salut Bronze	3,2274	0,0037
	Width	Salut Bronze~Salut Iron	−2,9764	0,0088

Table 4 Statistically significant results of Dunn's test for pairwise comparisons of width, length and depth variable among sites. P-values have been adjusted using the Bonferroni correction.

robustness (width), which is known to be a reliable proxy for comparisons between sites (Bormetti &Albarella 2024), the present data suggest that, at least at Salut, caprine size is smaller in Iron Age phases.

Figure 2 shows LSI boxplots, separately for taxa, sites and phases. Unfortunately, Bimah yielded insufficient data, so no relevant observation can be drawn. When examining the data for goats alone, a difference is observed between the Iron Age phase of Salut and Daba, where bones are larger both in length and width. Additionally, at Salut, a further difference in length is evident between the two phases, later specimens being smaller.

Sheep, on the other hand, show significant differences only in terms of robustness. These differences are particularly evident between Bronze Age and Iron Age specimens both between the two phases at Salut and between the Bronze Age phase at Salut and Daba.

When comparing the two species, for all sites and phases goats are significantly smaller than sheep as proved by Kruskal-Wallis test in Table 5. The observation can also be seen in the boxplots in Figure 2.

The scatterplot in Figure 3 illustrates the comparison between the shape of the astragali from the modern reference sample and those from archaeological sites in Oman and UAE regions.

It should be noted that the modern reference data from the Tübingen collection are very limited, which poses challenges for direct comparisons with the archaeological data. As a result, they were used solely to observe their distribution within the scatterplot of Figure 3, offering additional support for the morphological identifications of the archaeological astragali.

Also note that caution is needed when comparing archaeological data due to the different numbers of observations available for the two sites of Daba and Salut. As a first observation, in Figure 3 (top) goats show a broader distribution pattern, indicating greater variability in the measured traits, whereas sheep exhibit a more concentrated distribution, reflecting a narrower range of variation. Some overlap between the two taxa is present, with occasional goat values falling within the sheep dispersion range and vice versa. However, as mentioned above in the methodological section, such overlap is expected in this type of analysis (Davis 2017). It is also worth noting that the data from Salut (Iron Age) goats display a slightly different distribution compared to those from Daba, with lower values of the Dl/GLl index.

A similar pattern is observed in the UAE data of Figure 3 (bottom), where sheep and goats are also well differentiated within the scatterplot. The data from these sites cover a broad chronological range, spanning from the Iron Age to the contemporary period (see above). Moreover, the distribution of modern specimens appears to be slightly shifted to the lower left in the graph compared to the distribution of the archaeological specimens. However, the paucity of available data does not enable developing further considerations on the question. Also in the UAE, as expected, there are a few cases where goat values fall within the sheep dispersion area and vice versa.

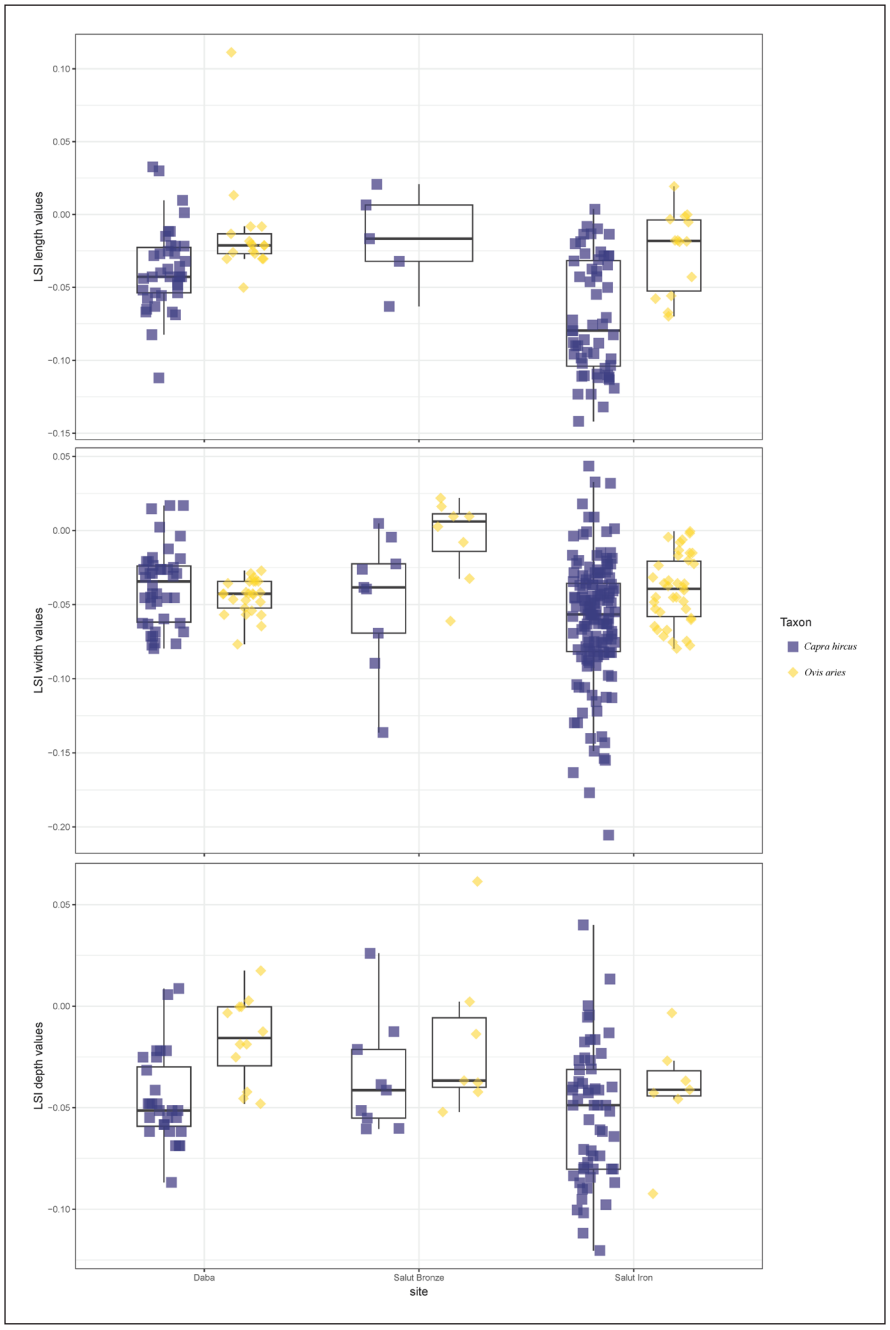

Figure 2 LSI boxplot of statistically significant results from the sites in Table 4 (Salut and Daba). The values for length (top), width (middle), and depth (bottom) are grouped by species, site and phase.

SITE	VARIABLE	CHI-SQUARED	df	p-value	η^2	f	MAGNITUDE
Salut Iron Age	Width	9.0108	1	0.0027	0.0385	0.2041	small
	length	13.637	1	0.0002	0.0608	0.2624	medium
	Depth	1.0574	1	ns			
Salut Bronze Age	Width	4.9042	1	0.0268	0.1952	0.5490	large
	Depth	1.4818	1	ns			
Daba	Width	1.82	1	ns			
	Length	9.6544	1	0.0019	0.1154	0.3840	medium
	Depth	12.39	1	0.0004	0.151867	0.4595	large

Table 5 Results of the Kruskal-Wallis test for the LSI width, length and depth values among taxa. P-values have been adjusted using the Bonferroni correction; ns = not significant.

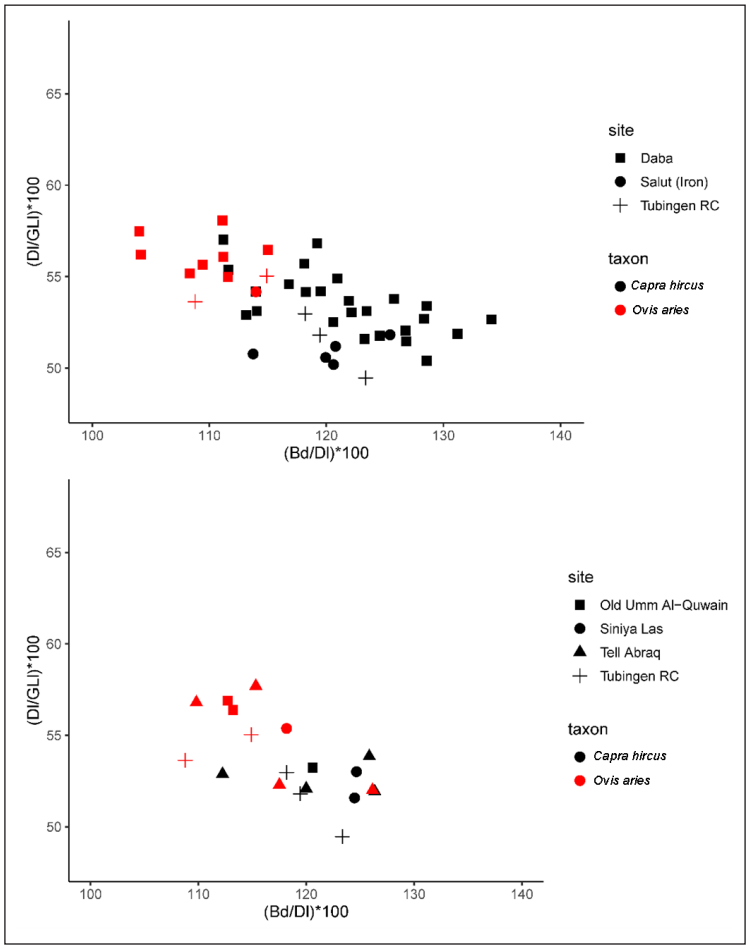

Figure 3 Astragali index scatterplot. Scatter diagrams of two indexes, Dl/GLl vs Bd/Dl calculated from Oman (top) and UAE (bottom) astragali. In the plot, symbols representing goats are black, while those representing sheep are red. The cross-shaped symbol (Tübingen RC) represents the modern reference.

Despite limited data, it is very interesting to note that these indices seem to provide reliable support for distinguishing between sheep and goats across all chronological periods. Overall, the biometrical analysis supports the determinations performed based on morphological criteria.

DISCUSSION

To summarize, the adaptive strategies adopted by prehistoric communities in South-East Arabia reflect an early and effective response to the challenges of arid environments. Recent studies on climate resilience in modern pastoral societies in arid sub-Saharan regions highlight the benefits of goats and camels over cattle, improving sustainability by reducing water use and emissions while maintaining protein supply (Rahimi et al. 2022). Similarly, archaeological evidence from South-East Arabia suggests that prehistoric herding strategies may have favored goats over other available fauna due to their ability to withstand extreme climatic conditions. Although increased robustness can be an adaptive response to arid environments in certain species, the success of caprines in South-East Arabia was likely due to their overall adaptability rather than skeletal robustness alone. Beyond their adaptability, goat milk served as both a reliable protein source and an essential component of hydration strategies in arid and rocky landscapes where water access was scarce. Rather than being merely a dietary staple, milk consumption likely fulfilled a dual function, supplying both hydration and vital nutrients to sustain human populations and to maximize resource efficiency in rocky landscapes characterized by limited water availability and fluctuating vegetation.

In addition, geographical location of the sites is essential. Indeed, the proximity to the sea increases the presence of marine resources at the sites, and this tendency probably remained constant throughout the different periods, as demonstrated in the literature on the Emirates. It is worth stressing that, apart from Jabal Al-Buhais and Wadi Al-Hilo, in the Emirates Al-Hajar, inland sites with studied faunal assemblages are lacking. According to zooarchaeological studies, land mammal bone finds are very rare in Neolithic inland sites due to very strong taphonomic factors (Uerpmann & Uerpmann 2000; Uerpmann et al. 2018). This lack of information does not allow speculation on herding economy in the internal territories of Oman during the Neolithic. In all likeliness, domestic ruminant exploitation was a well-

established practice on the coast, possibly at that time just aiming at protein surplus (Uerpmann & Uerpmann 2003; Mashkour at al. 2016).[11] Moreover, bovids seem almost completely absent till the Iron Age on the central Omani coast,[12] while in inland sites they were exploited already during the Bronze Age, as shown by Salut ST1.

Moving now to the results of the metrical study, the LSI analysis here developed and presented in Figure 2 shows a general trend of smaller goats compared to sheep in South-East Arabian prehistory (Table 5; Figure 2).

In addition, besides confirming previous observations on the particularly small size of Iron Age caprines at Salut (Strolin & Studer 2018), the study also adds new interesting insights to the topic by placing the evidence in a geographical and chronological perspective. Indeed, the present results indicate that the sheep and even more strikingly the goats from Salut Iron Age phases are smaller both compared to Salut Bronze Age caprines, but also compared to the caprines documented for the Iron Age at Daba.

Regarding the metrical analysis of caprine astragali, the faunal evidence from Oman and namely from Daba shown in Figure 3 (top) yielded a larger set of data for discussion. Daba sheep astragali have relatively higher antero-posterior depth values (Dl/GLl values). This result is consistent with the typically longer sheep metatarsi as compared to goats (Boessneck, Müller & Teichert 1964; Davis 2017). Indeed, considering the position and movement of the astragalus in bovids' limbs, Dl contributes to the limb length (Davis 2017). The same consistency is conversely observed in goat data: lower Dl/GLl values corresponding to shorter metatarsi. Moreover, the particularly low position in the scatterplot of Salut Iron Age goat astragali confirms the results of the LSI analysis (Figure 2) as for the smaller size of Iron Age Salut goats. In addition, the data from Oman goats tend to have relatively high Bd/Dl values, reflecting their broader build along the latero-medial axis. This trend seems to be also observable in the data from the South-East Arabian Peninsula in Figure 3 (bottom).

Despite the limitations of this study in terms of statistics, we would however like to raise some further points of reflection on the results achieved, that are beyond the scope of the present paper but may be possibly developed in future investigations. First, the faunal assemblage from Salut and, most importantly, the Iron Age assemblage, featured a significant predominance of females (Strolin & Studer 2018). Such a predominance of females may be at the origin of the observed overall smaller size of the animals in the archaeological sample shown in Figure 2.

In addition, the absence of imported items from distant areas in the Iron Age archaeological evidence of Salut suggests the site was more isolated and self-reliant compared to the Bronze Age phases. In Iron Age fauna as well, there is minimal evidence for imported taxa (Strolin & Studer 2018). Indeed, for the Bronze Age, long-distance connections and trade are widely documented by archaeological evidence (for instance imported pottery, seals, beads etc., see Avanzini 2015; Degli Esposti 2016; Frenez et al. 2016). As such, it cannot be excluded that this isolation and Salut's location inland to the Al-Hajar also prevented admixture with non-local populations presenting a more solid build, thus enhancing the specificities of local herds. A possible reduction in size along chronology between Bronze and Iron Age remains an open question.

When turning to the data from the northern part of the Emirates and in the Musandam peninsula, strategically located on an isthmus of land in the middle of the sea, the size and shape of caprines seem to be different from the inland area (Figure 2). One possibility is that this feature is related to diverse cultural and/or environmental conditions. The caprines belonging to the late Iron Age phase of deposition in Daba LCG2 tomb may reflect a society interconnected with the rest of the Gulf region, which is documented by the great number of imported objects among the grave goods (Frenez et al. 2021; Genchi, Ramazzotti & Larosa 2022). Moreover, it is possible to appreciate in Figure 3 a great variability of size and robustness also in the sheep and goats discovered in the Iron Age phase (IA II) at Tell Abraq in Umm Al-Quwain.[13]

The flat surrounding territory between the Al-Hajar Mountains and the sea may have improved the possibility of human/animal movement along the coast and contribute to developing short and middle-range exchanges. In this scenario, it is possible to suppose, conversely to the Early Iron Age phase of Salut, an easier and perhaps encouraged, mixture with non-local caprine populations in this part of the Arabian Peninsula. However, one must keep in mind that Daba animal remains are directly related to a specific ritual behavior, and as such may not entirely reflect local animal economy and livestock.

As a final remark, in the astragalus scatterplot of Figure 3 one can observe a more compact distribution of sheep values compared to goat values. Further research based on larger metrical datasets would be necessary to verify whether this represents a consistent trend. The observed difference in distribution might reflect greater morphological variability in goats and significantly lower variability in sheep astragalus measurements. This could be linked to selective breeding of sheep during the Iron Age (for specific traits? for ritual purposes at Daba? other reasons?) or to a different exploitation strategy applied to the two species (Davis 2017).

CONCLUSION

This study provides an exploratory analysis of faunal remains from different archaeological sites, inland and coastal, along the easternmost part of the Arabian

Peninsula (Oman and UAE), with a particular focus on the Bronze Age and Iron Age phases. It is the first comparative study of zooarchaeological data on sheep and goats that includes osteometry, with the full osteometrical unpublished dataset made available through this publication and the effectiveness of the metrical discrimination between sheep and goat astragali after Davis (2017) assessed also for the investigated geographical area.

This study underlines how coastal and inland sites differed in the exploitation of animal resources. Indeed, coastal communities mainly relied on marine resources and shifted to a more significant exploitation of domestic ruminants only in the Iron Age. A different picture could be drawn for inland communities, where domestic ruminants and mainly small stock constitute the core of animal economy already in the Bronze Age.

The LSI metrical analysis and statistical tests enabled the comparison of caprine sizes, namely based on the datasets of Salut and Daba Al-Bayah. The study showed the smaller size of the goats compared to sheep in both sites. Moreover, the caprines, and in particular the goats, from the Iron Age inland site of Salut turned out to be significantly smaller in comparison with the Iron Age coastal site of Daba. Considering the different geographical location of the two sites and their chronological phasing, significant insights were provided and new questions raised on ancient livestock in the South-East Arabian Peninsula. These first results and the valuable data generated lay the foundation for future in-depth research, encouraging the integration of more extensive datasets and the application of advanced analytical techniques.

NOTES

1 It is not possible, in the present paper, to consider all the metrical data collected, also available in other published works, on the osteological remains belonging to Neolithic, Umm an Naar and Hafit period on the coast, because they are not statistically sufficient. Hence, we can't include in this evaluation the scarce osteometrical data from domestic animals retrieved in Ras al-Hadd HD-5 (Borgi & Maini 2020) e HD-1 (Maini under study) e di Ras al-Jinz RJ-2 (Bökönyi 1998) or RJ-3 (De Rorre et al. 2020).

2 Excavations at Salut were carried out between 2004 and 2019 by the IMTO (Italian Mission To Oman) of the University of Pisa under the direction A. Avanzini and with the support of the former Office of H.E. the Advisor for H.M. the Sultan for Cultural Affairs (Degli Esposti 2016; Avanzini & Degli Esposti 2018).

3 Excavations at Daba Al-Bayah were conducted between 2013 and 2022 under the direction of F. Genchi on behalf of the Ministry of Heritage and Tourism (2013–2015) and on behalf of Sapienza's MAGPAG Project – Sapienza Archaeological Mission in the Arabian Peninsula and Gulf – F. Genchi and M. Ramazzotti (2017–2022) (Genchi et al. 2018; Genchi, Ramazzotti & Larosa 2022).

4 Excavations at Bimah BMH2 were carried out between 2014 and 2017 by the University of Naples "L'Orientale" under the direction of R. Loreto (Loreto 2018).

5 The general scarcity of coastal Iron Age sites deeply studied represents a well-known problem in literature. Currently, Bimah-BMH2 is the only late Iron age site where the entire animal bone sample has been studied (Maini & Loreto 2022).

6 The new project of archaeological investigation at Tell Abraq was launched in 2019 under the field direction of M. Degli Esposti (Italian Archaeological Mission in Umm al-Quwain – IAMUQ) in collaboration with the Tourism and Archaeology Department of Umm al-Quwain (TAD-UAQ).

7 The Sīnīya Island Archaeology Project (SIAP) started the exploration of Sīnīya Island's archaeological landscape in 2021, under the direction of Sheikh Majid bin Saud Al Mu'alla, Chairman of TAD-UAQ, in collaboration with the Ministry for Culture and Youth, UAE University, the IAMUQ and New York University. The research activities are directed by T. Power and M. Degli Esposti with the support of R. Hoyland and R. Houssein Kannouma. Fieldwork was led by archaeologists of the IAMUQ team assisted by students from the UAE University and the New York University.

8 During data analysis, the measurements from three caprine bones belonging to the faunal assemblage collected in the Old Umm al-Quwain town, dated to the 18th century AD and discovered on Siniya Island, were considered for comparison (see Supplement S2).

9 On fish remains see Iwaszczuk: 224–226 in Power et al. 2024.

10 On mammal remains see Maini: 223–224 in Power et al. 2024.

11 These two publications serve as examples; it is recommended to also consider the extensive bibliographic references cited within these articles.

12 S. Bökönyi reported seven bone fragments that could belong to *Bos taurus* (Bökönyi 1992). After a complete review of the faunal assemblage discovered at RJ-2 carried out by E. Maini (Maini in preparation), it was not possible to confirm this determination.

13 As previously mentioned, the study of the numerous faunal remains from Tell Abraq is ongoing, in parallel with the excavation campaigns, and is focusing on the Iron Age phases (mainly Iron Age II). However, data analysis is still in progress, and a detailed analysis of the specific context will be provided in the future (Maini in preparation).

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplementary file S1.** Osteometric data and LSI values. DOI: https://doi.org/10.5334/oq.149.s1
- **Supplementary file S2.** Astragalus measurements for species discrimination. DOI: https://doi.org/10.5334/oq.149.s2

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Elena Maini carried out the zooarchaeological analyses on faunal remains from Daba Al-Bayah, Bimah BMH2, Tell Abraq, and Siniya Island, while Laura Strolin carried out the zooarchaeological analyses on faunal remains from Salut territorial compound in the Sultanate of Oman. Matteo Cianfoni elaborated all the statistical analyses included in this contribution. All authors have contributed equally to writing and reviewing the text.

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