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Palaeodietary reconstruction of wild and domestic goats using dental microwear texture analysis. A case study from two early Neolithic sites in the southern Levant

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ABSTRACT

Dental microwear (DMA) is a tool used for the palaeodiet reconstruction of animals in Archaeology. The use of this proxy on domestic ungulates provides valuable information to reconstruct livestock strategies, yet it presents several methodological limitations. Most studies have been carried out using low-magnification DMA and the interpretations often relied on comparisons with databases of extant wild ungulates. In addition, several studies have highlighted challenges in discerning diets in extant domestic caprines. In parallel, dental microwear texture analysis (DMTA) – a quantitative methodology based on 3D micro-texture height maps – has shown better discrimination. In this paper, we explore the capacity to distinguish four different management strategies of domestic goats (*Capra hircus*) and three species of wild ibexes (*Capra nubiana*, *C. pyrenaica* and *C. ibex*) using DMTA. Results revealed good discrimination among extant domestic goat populations and between wild and domestic goats. This new dataset was subsequently used to characterise the palaeodiet of archaeological goats from two Pre-Pottery Neolithic B sites in the southern Levant. Preliminary findings suggest evidence of human intervention in goats at least during the early 8th millennium BCE. In addition, incorporating various current management strategies has enhanced our understanding of early goat domestication in southern Levant.

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Introduction

Sheep and goats played an important role in the late Prehistoric farming societies throughout the Mediterranean Basin. Since the Neolithic to the Iron Age, caprines are the predominant species – over pigs and cattle – in the archaeological faunal assemblages in many regions of the western and eastern Mediterranean (e.g. Halstead 1981, 2006; Saña 1998; Albarella et al. 2006; Albizuri et al. 2010; Trentacoste et al. 2018, 2021; Nieto-Espinete et al. 2020, 2021). Their major role in animal management since the Neolithic period makes caprines a valuable source of information to understand the husbandry practices in late Prehistory.


From traditional lines of evidence of zooarchaeology (e.g. taxonomic and anatomic representation and mortality profiles), it is possible to address issues such as the type of economical exploitation (e.g. meat or milk) (e.g. Stein 1987; Helmer and Vigne 2004; Helmer et al. 2005, 2007) or the composition of the herd (e.g. Grayson 1984, Davis 1987). However, some aspects of the livestock management practices such as animal food provisioning (e.g. type of pasture and foddering strategies), the type of exploitation (i.e. intensive or extensive) or the landscape use require further analyses.

The reconstruction of animal palaeodiet can provide relevant information about the strategies used by herders and farmers to feed animals and, therefore, on the type of pasture, the impact on

the environment, the foddering strategies and the human intervention on animal diet in the early stages of animal domestication (e.g. Makarewicz et al. 2016; Yamada et al. 2018; Jiménez-Manchón et al. 2023). Stable isotope analysis, particularly of carbon isotope ratio ($\delta^{13}\text{C}$) from or dentine collagen, or tooth enamel, can be used to explore animal feeding strategies (e.g. Balasse 2002; Tornero et al. 2018; Navarrete et al. 2019). The carbon is incorporated from the food and water intake by the animal and the $\delta^{13}\text{C}$ values vary according to the type of plants (e.g. Balasse 2002; Balasse et al. 2012). In addition, the integration of stable oxygen and carbon isotopes can provide insights into the seasonality of diet and water resources and climate (e.g. Makarewicz et al. 2017; Hadjiloumou et al. 2019; Trentacoste et al., 2020). There are, however, methodological limitations. This is a destructive method, requiring sampling preparation, which often results in a reduced number of analysed samples. The studies carried out on collagen are also constrained by its not always good preservation in e.g. arid regions like in the Near East (e.g. Grupe 1995; Miller et al. 2019). In contrast, studies performed on tooth enamel, which presents a better preservation than collagen, only record isotopic changes that occurred during the mineralisation of the tooth. Furthermore, isotopic signal can be affected by the enamel mineralisation process, which consists of two phases: secretion and maturation (Green et al. 2017).

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Dental microwear analysis (DMA) is an additional powerful tool for palaeodietary reconstruction. This non-destructive tool is based on the analysis of microfeatures produced by ingested food items on the dental occlusal surface in the last weeks before the animal death (Walker et al. 1978; Teaford and Walker 1984; Gordon 1984; Grine 1986). This method is largely used for dietary reconstruction of wild ungulates from Pleistocene contexts to explore human hunting seasonality (e.g. Rivals and Deniaux 2005, 2005, 2015; Sánchez-Hernández et al. 2015), and ecological and environmental reconstruction (e.g. Calandra et al. 2016; Uzunidis 2020, Kubo and Fujita, 2021; Berlioz et al. 2022). However, the number of studies conducted on DMA on domestic ungulates is yet scarce, although in the last decade interest in palaeodiet reconstruction of domestic species has grown (e.g. Rivals et al. 2011; Rieau 2014; Mainland et al. 2016; Gallego et al. 2017, 2020; Jiménez-Manchón et al. 2019, 2020, 2023; Ibáñez et al. 2020; Lespes 2020; Sierra et al. 2021; Valenzuela-Suau et al. 2022). These works have shown several methodological limitations in the use of DMA on domestic ungulates. Firstly, most of these works have used Low-Magnification Dental Microwear Analysis (LMDA). This technique, based on the qualitative identification and quantification of microfeatures (i.e. scratches and pits) on the tooth surface, has been questioned about intra- and inter-observer error (Mihlbachler et al. 2012; De Santis et al. 2013), although this error is not statistically significant with well-trained observers (Sempredon et al. 2004; Sempredon and Rivals 2007). Secondly, most of the interpretations of the results obtained by LMDA have been carried out with a database spanning different taxa and groups including artiodactyls and perissodactyls (Solounias and Sempredon, 2002; Sempredon et al. 2004). In an attempt to overcome these limitations, several studies have tried to discriminate between different extant herd management strategies, mainly in domestic sheep, using reference collections (e.g. Rieau 2014; Ibáñez et al. 2020) or experimental works (Gallego et al. 2020). These studies have noted the high difficulty to discriminate extant diets in domestic species using this technique. In this sense, Ibáñez et al. (2020) analysed two groups of extant ewes that were differently fed: one roaming on rangeland, combining Mediterranean forest and meadows, and the other on grasslands, using both LMDA and DMTA (Dental Microwear Texture Analysis). The results of this comparison showed better discrimination using DMTA compared to LMDA (Ibáñez et al. 2020).

DMTA is a technique based on quantitative analysis of the microtexture wear of the dental occlusal surface using confocal microscopy (Scott et al. 2005; De Santis et al. 2013). This method offers the advantage of gathering 3D surface texture representations at high magnifications from which it is possible to obtain quantitative parameters: ISO 25178 (International Organisation for Standardization 25178; Schulz et al. 2010; Purnell et al. 2012; Calandra et al. 2012) and SSFA parameters (Scale-Sensitive Fractal Analysis; Scott et al. 2005, 2006). Unlike previous techniques, (1) DMTA is a reproducible method that reduces intra- and inter-observer errors (De Santis et al. 2013), and (2) it is a technique with which it is easier to discriminate different diets of domestic animals (Ibáñez et al. 2020).

In spite of the advantages that this technique offers to domestic animal palaeodiet reconstruction, its use on extant domestic ungulates is still uncommon (e.Merceron et al. 2016; Ramdarshan et al. 2017; Ackermans et al. 2020; Louail et al. 2021). These works were conducted in controlled-feeding experiments, primarily focusing on specific factors such as the effect of dust and grit on dental microwear. Consequently, the diet of these domestic ungulates was entirely controlled in experimental settings and does not reflect the diversity of animals in current or past management strategies. Therefore,

studies that could characterise and discriminate diets of extant management strategies using DMTA are missing. If successful, such studies will then be applied to archaeological contexts.

In a previous work (Jiménez-Manchón et al. 2023), domestic goats that fed in wooded and overgrazed areas were successfully discriminated from various species of wild ibexes using DMTA. The use of a discriminant analysis to a collection of early Neolithic goats from Tell Qarassa North (southern Syria) and Kharaysin (northern Jordan) indicated that some individuals from the second site show similar pattern that the domestic goats. This information, besides the high variability in DMTA values for Kharaysin, suggested that human intervention in goat feeding could have taken place there at the beginning of the 8th millennium cal. BCE or even before. However, one major issue limited the scope of this preliminary, though promising, study. Only one type of domestic management was included in the predictive model, so it was not clear how various feeding strategies of domestic goats might affect the model's ability to discriminate wild and domestic diets. Furthermore, it was not possible to determine the specific type of management strategy that herders may have been employed to feed goats.

The present work makes a significant contribution on this topic. In this paper, we explore the use of DMTA to characterise and discriminate different management strategies of four modern domestic goat populations with known diets. Our research focused on exploring how dental microwear patterns vary according to pasture system. In addition, the four management strategies of domestic goats were compared with the diet pattern of three different wild species. The main objective is to explore potential similarities and differences among these goat populations. The models derived from DMTA were then used to characterise the dietary patterns of goats (*Capra cf. aegagrus*) from two Pre-Pottery Neolithic sites in the southern Levant: Kharaysin (Zarqa, Jordan, ca. 8800–7500 cal. BCE) and Tell Qarassa (As-Suweida, Syria, ca. 8700–8200 cal. BCE).

We used two types of parameters: SSFA and ISO 25178. On the one hand, SSFA is a method to quantify the micro-texture surface by analysing the changes across scales. Three parameters have been considered: area-scale fractal complexity (Asfc), length-scale anisotropy of relief (epLsar) and heterogeneity of complexity (HASfc). On the other hand, 30 standardised ISO parameters related to height, volume, area and function, used to analyse 3D surface texture, were considered. In this work, in addition to the methodology commonly used to characterise animal diet using SSFA and ISO parameters, we explored alternative methods to present ISO parameters such as bivariate graphs.

Consequently, this paper delves into the potential of DMTA in discriminating the dietary behaviours of modern wild and domestic goats with known diets and geographic origin. The development of this database through DMTA constitutes a valuable tool for interpreting dental microwear in archaeological and palaeontological contexts. Furthermore, we investigated the results obtained to characterise the diet of ancient goat populations, in order to enhance our understanding of the early husbandry practices in the Near East.

Material and methods

The reference collection

A total of 94 specimens have been analysed, of which 51 were domestic and 43 wild goats. The domestic goats (*Capra hircus*) were managed according to traditional systems but with different

exploitations. They came from four different locations with different management strategies: the first group (CH1) of goats fed in the northern Saharan steppe (Algeria), the second group (CH2) in wooded and overgrazed areas in southern Catalonia (north-eastern Iberian Peninsula), the third one (CH3) on grasslands in the southern side of the Pyrenees (north-eastern Iberian Peninsula), and the last one (CH4) on wooded areas in the Causse of Larzac (southern France).

The wild specimens corresponded to three other species: *Capra nubiana* (CN) from the Near East; *Capra ibex* (CI) from the Alps; and *Capra pyrenaica* (CP) from the southern Iberian Peninsula (Figure 1). No goats were deliberately killed for this study. The wild goats were from the osteological collection of several museums, and the domestic ones either naturally died or the mandibles were recovered from slaughterhouses or breeders.

CH1. Extensive grazing on steppe vegetation (northern Sahara, Algeria)

The collection consisted of 18 adult female domestic goats of the Arabia breed, the most important local breed in Algeria (Manallah 2012). The specimens came from the region of Laghout (northern

Sahara, Algeria) (Ridouh 2021). The region is dominated by steppes with a semi-arid climate, experiencing increasing desertification and degradation of pastures (Belala et al. 2018), with average temperatures ranging from 10° to 34°C. These goats are exploited for meat and they do not receive additional supplies of fodder. Regarding the diet, goats grazed in steppe vegetation which is mainly composed of grasses such as feather grass (*Stipa tenacissima*) and esparto grass (*Lygeum spartum*) (Dalila and Slimane 2008). The season of death is unknown for all individuals.

CH2. Extensive grazing on wooded and overgrazed areas (southern Catalonia, north-eastern Iberian Peninsula)

A collection of 15 domestic goats (four males and 11 females) of the Blanca de Rasquera breed was sampled. Four specimens are mixed with the Granadino-Murciana breed. The goats came from two close areas in southern Catalonia presenting the same environment (province of Tarragona). The vegetation of this environment is composed of woody plants: holm oak (*Quercus ilex*), hermes oak (*Quercus coccifera*), rosemary (*Salvia rosmarinus*), heather (*Erica* sp.), scorpion broom (*Genista scorpius*), shrubby hare's-ear (*Bupleurum fruticosum*), wild madder (*Rubia peregrina*), juniper















Goat species	Status	Dietary regime/management strategy	Geographical location	Climate
 <i>Capra hircus</i>	Domestic	Algerian steppe 	Laghout (Algeria)	Semi-arid
 <i>Capra hircus</i>	Domestic	Overgrazed wooded area 	Province Tarragona (northeastern Iberian Peninsula)	Mediterranean
 <i>Capra hircus</i>	Domestic	Grassland 	Gavàs - Catalan Pyrenees (northern Iberian Peninsula)	Mountain (1200 m)
 <i>Capra hircus</i>	Domestic	Grasses + woody plants 	Larzac (southern France)	Mountain (600-900 m)
 <i>Capra ibex</i>	Wild	Grasses + woody plants 	Val d'Aosta (northeastern Italy)	Mountain (1000 - 3500 m)
 <i>Capra nubiana</i>	Wild	Grasses + woody plants 	Sinai and southern Jordan	Arid and Mediterranean steppe
 <i>Capra pyrenaica</i>	Wild	Woody plants 	Southern Iberian Peninsula	Mountain (1000 - 2800 m)

Figure 1. Goat species, status, dietary regime and management strategy, geographical location and climate for each modern goat group. For CH1 and CH2, the circles in the dietary regime/management column indicate the intake of dust/grit.

(*Juniperus communis*) and grass plants: nut grass (*Cyperus rotundus*) and spiny-head mat-rush (*Lomandra longifolia*) (Jiménez-Manchón et al. 2023). The flock grazed in a similar area throughout the year and, consequently, goats were fed in an overgrazed environment. These goats did not receive additional supplies of fodder and feed on available vegetation in wooded areas (500–1000 m). Given that the availability of woody plants is poor in this overgrazed environment, the intake of herbaceous plants by goats was dominant (Jiménez-Manchón et al. 2023). The specimens were collected in spring ($n = 3$), summer ($n = 9$), and autumn ($n = 3$) 2021.

CH3. Extensive mountain grazing on grasses (southern side of Pyrenees, northern Iberian Peninsula)

Three female domestic goats of Alpine breed were sampled. They originate from Gavàs, located on the southern side of the Pyrenees (Pallars Sobirà, northeastern Spain), and were devoted to milk exploitation. The goats died in winter 2021. During this season, they had seven hours per day of pasture in the meadow, feeding only on grasses (e.g. *Arrhenatherion elatioris* associations) in high mountain areas (>1200 m) with average winter temperatures ranging between -7° and 2° C (López-i-Gelats et al. 2015). They received a small amount of supplement of uncultivated meadow grasses.

CH4. Extensive browsing on wooded areas (Larzac, southern France)

A set of 15 domestic goats coming from the Causse of Larzac (southern France) was sampled. The sex and the season of death are unknown for all individuals. The flock browsed in wooded areas (600–900 m) on the plateau of Causse of Larzac, with a supramediterranean bioclimate. In this area, woody plants dominate, such as holm oak (*Quercus ilex*), pubescent oak (*Quercus pubescens*), beech (*Fagus sylvatica*), and hazelnut (*Corylus avellane*), along with the presence of grasses (Prioton 1970). The domestic goats did not receive additional supplies of fodder.

CN. *Capra nubiana* (Sinai Peninsula and southern Jordan)

We sampled 12 adult Nubian ibexes (three females, seven males and two of unknown sex) from three localities (i.e. Wadi Ihmed, Wadi Adani and Wadi Leithih) from the Sinai Peninsula (eastern Egypt) and the region of Petra (southern Jordan). The specimens, curated at the Zoological Museum of Strasbourg in France, were collected between 1893 and 1911 between spring ($n = 2$) and summer ($n = 3$). The season of death of the rest of the individuals ($n = 7$) is unknown. The region is characterised by heterogeneous landscapes, transitioning from arid to steppe Mediterranean woodlands. In the arid regions, vegetation is scarce, and it is dominated by shrubs (*Haloxylon persicum* and *Retama raetam*) with patches of *Acacia*. In the steppe regions, there is a cover of grasses and *Artemisia* plants, as well as woody plants such as *Moringa*, juniper (*Juniperus*), *Pistacia* and *Phoenix* (Palmer et al. 2007). The Nubian goat population had a flexible diet, with a tendency to grazing (Hackham and Ritte 1991).

CI. *Capra ibex* (Val d'Aosta, northern Italy)

Twelve adult Alpine ibexes (five females and seven males) from Val de Cogne in Val d'Aosta (north-western Italy) were analysed. The specimens, curated at the Zoological Museum of Strasbourg in France, were collected in 1897. The season of death is unknown for all specimens. Alpine ibexes can live at elevations ranging from 1000 to 3500 m. The vegetation is characterised by a gradient based on altitude. Above 1800 m, the vegetation is rich in woody plants such as *Pinus sylvestris*, *Laric decidua* and *Betula alba*. To a lesser extent, there are

grasses and other herbaceous plants. Below 1800 m, meadows (*Avenula pubescens*, *Gentiana lutea* and *Galium glaucum*) and steppe-like communities (*Centaurea scabiosa*, *Galium verum*) are more common (Pini et al. 2017). This species has a diet dominated by grasses and other herbaceous plants, although their diets may vary according to the season (Couturier 1962; Zingg 2009; Parrini et al. 2009).

CP. *Capra pyrenaica* (southern Iberian Peninsula)

A set of 19 adult Iberian ibexes (14 females and five males) from Sierra Nevada and Sierra de Cazorla (southern Iberian Peninsula), curated at the Estación Experimental de Zonas Áridas-CSIC (Almería, Spain), the Estación Biológica de Doñana-CSIC (Seville, Spain) and the Parque Nacional de Sierra Nevada (Granada, Spain), were sampled. The osteological collection was collected between 1987 and 2007 in spring ($n = 7$), summer ($n = 7$), and autumn-winter ($n = 3$). The season of death is unknown for three individuals. The vegetation depends on the altitude. Above 2700 m, woody plants such as *Festuca clementei* and *Arenaria nevadensis* dominate. Below, there are *Juniperus* communities, *Pinus sylvestris*, Thyme-pasture communities and herbaceous plants. This goat species tends to consume ligneous plants, such as *Quercus ilex*, *Pinus nigra* and *Thymus zygis*. Among the grasses, the consumption of *Brachypodium* stands out (Martínez et al. 1985; Cuartas and García-González 1992; Cuartas et al. 1996; Martínez 2000).

Archaeological materials

The archaeological material studied originated from two Pre-Pottery Neolithic sites situated in the southern Levant: Kharaysin (Zarqa, Jordan) and Tell Qarassa (As-Suweida, Syria) (Figure 1). Kharaysin is a large site around 25 ha and it is located in north-western Jordan (Ibáñez et al. 2015). Excavations conducted at Kharaysin have revealed four chronological sequences: 1) Late Pre-Pottery Neolithic A (PPNA, beginning of the 9th millennium cal. BCE), 2) Early Pre-Pottery Neolithic B (EPPNB, second half of the 9th mill. cal. BCE), 3) Middle Pre-Pottery Neolithic B (MPPNB, beginning of the 8th mill. cal. BCE), and 4) Late Pre-Pottery Neolithic B (LPPNB, end of the 8th mill. cal. BCE). The preliminary zooarchaeological study indicates the progressive increase in the frequency of goats at the expense of gazelles from the lower to the upper layers. In light of these findings, the results obtained from a DMTA analysis suggest the possible coexistence of managed and wild goats during the MPPNB phase (Jiménez-Manchón et al. 2023). In this work, we selected a total of 13 goats from Kharaysin, excluding specimens affected by taphonomical alterations.

Tell Qarassa, situated in the southern Syria, is an Early Pre-Pottery Neolithic B site occupied between c. 8700 and 8200 cal. BCE (Ibáñez et al. 2010). The excavations conducted in 2009 and 2010 revealed buildings dating from the mid-9th millennium cal. BCE. According to the zooarchaeological analysis, goats prevailed, followed by other ungulates such as gazelles, wild boars and aurochs (Ibáñez et al. 2010). DMTA was performed on three goat specimens that did not exhibit taphonomical alterations.

The palaeoenvironmental data available for the southern Levant revealed the existence of varied ecological niches (e.g. Asouti et al. 2015). Kharaysin and Qarassa regions were characterised by a combination of wooded steppe components and riparian taxa (Arranz-Otaegui et al., 2017). Notably, eudicotyledonous plants like *Pistacia*, *Amygdalus* and *Quercus*, and, to a lesser extent, grasses were present in the surrounding vegetation.

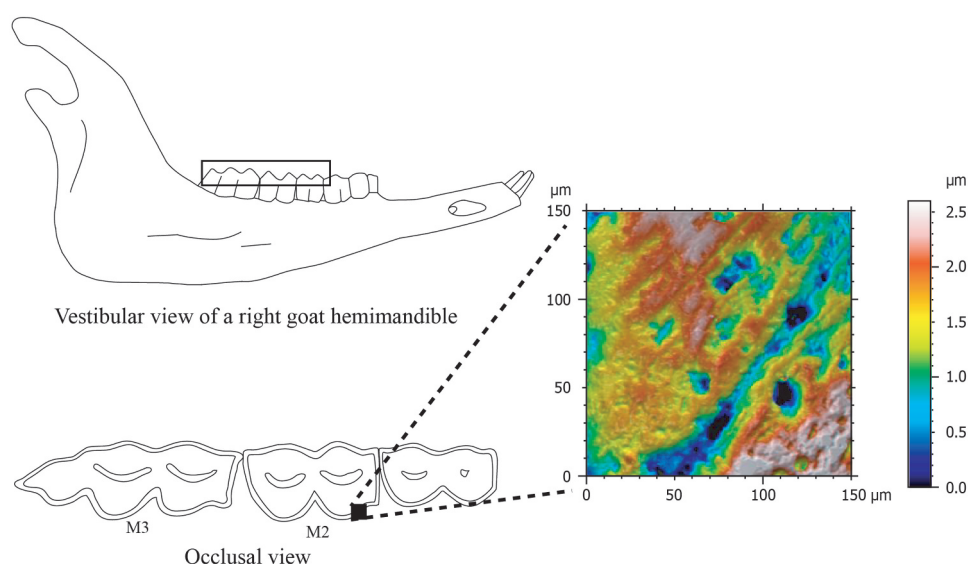


Figure 2. Exemplary occlusal view from a right hemimandible of goat, and topography texture enamel surface (false colour elevation map) of mesiobuccal facet of a second lower molar protoconid.

Dental microwear analysis

The occlusal surface of the mandible teeth was carefully cleaned using acetone and 96% ethanol. For this purpose, we used cotton wool to avoid damaging the surface. Then, we moulded the occlusal surface using high-precision polyvinylsiloxane (President Light Body, Coltene Waledent). Two moulds were taken: the first one was made to remove the remaining dust and was discarded, and the second was kept for DMTA analysis.

DMTA was conducted on the mesio-buccal facet of the second lower molar (M2) protoconid (Figure 2). A single facet was selected since the inclusion of other may increase the sample variance and may make differentiation between dietary groups difficult (Ramdarshan et al. 2017). When it was not possible, the analysis was extended to the hypoconid. The moulds were analysed with a white-light scanning confocal microscope (Sensofar Plu Neox) using a $\times 50$ (0.80 NA) objective housed at the Institutió Milà i Fontanals-CSIC (Barcelona, Spain). For each facet, an area of $150 \times 150 \mu\text{m}$ was selected and measured using MountainsMap 7 software (Digital Surf) (Figure 2). The extreme measured points were eliminated (upper and lower 0.5%) to remove the outliers. The tooth occlusal surface generally has a curved morphology. The least-square (LS) plan method was used to correct the lack of horizontality of the sample. Consequently, the form was eliminated using a polynomial function (power 8; Francisco et al. 2018). Archaeological teeth with taphonomic features were excluded from the study based on previous studies (Uzunidis et al. 2021; Weber et al., 2022).

SSFA and ISO 25178 parameters were obtained from Mountains 7 (Table 1). Firstly, three SSFA parameters were measured: complexity (Asfc), anisotropy (epLsar) and heterogeneity of complexity calculated through 9 cells (HASfc9) (Scott et al. 2005, 2006). Secondly, a total of 30 ISO parameters were considered (Table S1). These parameters are pooled to height (e.g. Sq, Sp and Sa), function (Smr), space (e.g. Str), volume (e.g. Vv, Vmp) and area (Sda and Sha).

Statistical analysis

According to the objectives of this study, two datasets have been analysed: the first focused only on the diet discrimination of four

domestic populations, while the second included both the four domestic and the three wild populations. For both datasets, the statistical procedure was as follows.

These values were explored using bivariate plots, indicating the mean and standard error of mean, similarly to previous works (e.g. Ramdarshan et al. 2017). The presence of significant differences was tested through ANOVA's test and Tukey's pairwise comparison. ISO Parameters were log-transformed to increase normality and homoscedasticity (Francisco et al. 2018). The presence of significant differences ($p \leq 0.05$) among the four groups of domestic goats, and the seven groups of wild and domestic goats was tested using an analysis of variance (ANOVA). When homogeneity of variance (Levene's test) showed significant differences, Welch's ANOVA was used. A Linear Discriminant Analysis (LDA) with cross-validation, based on parameters that present significant differences, was constructed. When Box's M was violated ($p \leq 0.05$), a Quadratic Discriminant analysis (QDA) was performed. The significance of discriminant analysis was assessed using Wilk's Lambda ($p \leq 0.05$). Consequently, the predictive model obtained for wild and domestic goats was used to classify the archaeological specimens from Kharaysin and Qarassa sites.

We explored the use of bivariate graphs based on 25178 ISO parameters. For this purpose, a Tukey's post-hoc test based on ISO variables was carried out on the seven groups of modern wild and domestic goats (Table S5). The parameters showing the largest differences in the four main categories (height, function, volume and feature) of 25178 ISO parameters were selected. The statistical procedures were carried out using IBM SPSS 26 statistics software®.

Results

Dental microwear pattern of domestic goat management strategies

SSFA parameters were explored using two bivariate plots (Figure 3). ANOVA's test detected significant differences in complexity (Asfc) (Table S1.1). No significant differences were found in heterogeneity (HASfc9) and anisotropy (epLsar). Goats managed in the Laghouat steppe (CH1) presented the lowest complexity values (Mean Asfc = 1.14), whereas goats managed in the more wooded vegetation

Table 1. Description and functional groups of the ISO 25,178 and SSFA parameters.

Abbreviation	Description	Functional group
epLsar (SSFA)	Anisotropy	Direction
Asfc (SSFA)	Area-scale complexity	Complexity
HAsfc9 (SSFA)	Heterogeneity	Heterogeneity of complexity
Sq (ISO parameter)	Root mean square height	Height
Sku (ISO parameter)	Kurtosis of the height distribution	Height
Sp (ISO parameter)	Maximum peak height	Height
Sv (ISO parameter)	Depth between the mean plane and the deepest valley	Height
Sz (ISO parameter)	Height between the highest peak and the deepest valley	Height
Sa (ISO parameter)	Arithmetic mean height	Height
Smr (ISO parameter)	Peak material proportion	Functional
Smc (ISO parameter)	Inverse areal material ratio	Plateau size
Sal (ISO parameter)	Auto-correlation height	Density
Str (ISO parameter)	Texture aspect ratio	Spatial
Vm (ISO parameter)	Material volume at a given material ratio	Volume
Vv (ISO parameter)	Void volume	Volume
Vmp (ISO parameter)	Material volume of the core at given material ratio	Volume
Vmc (ISO parameter)	Material volume of the core at given material ratio	Volume
Vvc (ISO parameter)	Void volume of the core	Volume
Vvv (ISO parameter)	Dale void volume	Volume
Spd (ISO parameter)	Density of peaks	Feature
Spc (ISO parameter)	Arithmetic mean peak curvature	Feature
s10z (ISO parameter)	Ten-point height	Height
s5p (ISO parameter)	Five-point height	Height
s5v (ISO parameter)	Five-point pit height	Height
Sda (ISO parameter)	Closed dale area	Area
Sha (ISO parameter)	Closed hill area	Area
Sdv (ISO parameter)	Mean dale volume	Feature
Shv (ISO parameter)	Mean hill volume	Feature
Sk (ISO parameter)	Core height	Functional
Spk (ISO parameter)	Peak reduced height	Functional
Svk (ISO parameter)	Reduced dale height, Reduced valley depth	Functional
Smr1 (ISO parameter)	Low peak material portion	Functional
Smr2 (ISO parameter)	High peak material portion	Functional

(CH4) presented the highest (Mean Asfc = 2.6). The groups CH2 and CH3 (i.e. goats managed in overgrazed and grassland areas) presented intermediate values of complexity (Table 2). These results indicate that the higher consumption of woody plants by goats from the Causse of Larzac increases complexity (Asfc), and the higher intake of grasses and dust/grist by goats from the Laghouat steppe reduces it. Concerning heterogeneity (HAsfc9) and anisotropy (epLsar), although no significant differences were found, goats managed in grasslands (Pyrenees) showed the lowest values for both parameters. It is worth noting that goats grazing in overgrazed vegetation (CH2) presented higher values than the population fed on steppe areas (CH1) (Figure 3 and Table 2).

A Quadratic Discriminant Analysis was performed on the basis of the ISO parameters that significantly differ (Table S1.2). The predictive model showed a correct cross-validation classification of 74.5% of the individuals. Goats managed in grassland in the Pyrenees (100%) were the best classified. The other groups were similarly classified between 72.2% and 73.3% (Table 3).

In the QDA texture-dietary plot (Discriminant Function 1 = 51.5%, Discriminant Function 2 = 28.5%), goats managed in Algerian steppe and overgrazed areas generally occupied positive values along the Discriminant Function 1 (Figure 4), while goats that grazed in grassland vegetation (Pyrenees) and in the Causse of Larzac had negative values. According to the discriminant coefficients (Table S1.2), the texture surface of goats managed in Laghouat steppe and overgrazed vegetation is characterised by less volume (Vm) and roughness (e.g. Sq).

Dental microwear pattern of wild ibexes and goat management strategies

SSFA values of wild ibexes and domestic goats are presented in Figure 5. ANOVA's test detected significant differences in complexity (Asfc) and heterogeneity of complexity (HAsfc9), with no differences in anisotropy (epLsar) (Table S1.3). All three groups of wild ibexes showed higher complexity (Asfc) values than domestic goats ($3.34 \leq \text{Mean} \leq 5.0$). Among the wild ibexes, CN had the lowest complexity values and CP presented the highest ones. Concerning heterogeneity, ibexes from the Near East (CN) and the Alps (CI), characterised by a great intake of ligneous plants compared to the other wild goat populations, presented the lowest values. In contrast, domestic goat managed in grassland (CH3) had the lowest values. The other goat groups displayed intermediate values (Figure 5 and Table 2). The Tukey's pairwise comparison revealed significant differences in complexity (Asfc) among various groups of and domestic goats (S5), such as CI and CH2, CN and CH2, CP and CH4. Significant differences have only been found between two groups of domestic goats (CH4 and CH1). Regarding heterogeneity (HAsfc9), differences have been observed between modern groups of wild and domestic goats (i.e. CN and CH3, CP and CH3, CP and CH4, CN and CH4).

A Quadratic Discriminant analysis was performed based on the ISO parameters that significantly differ between the 7 groups (Table S1.3). 72.3% of individuals were correctly classified according to the QDA (Table 4). Domestic goats managed in grasslands (CH3) and

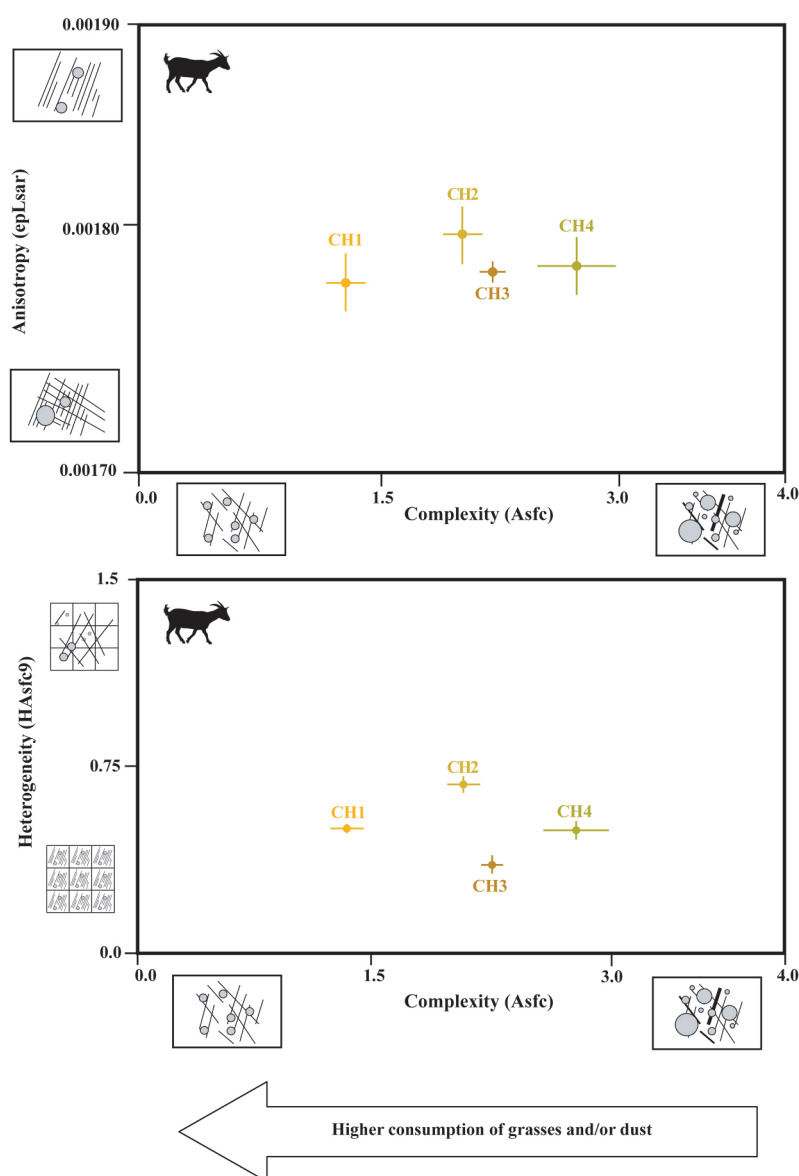


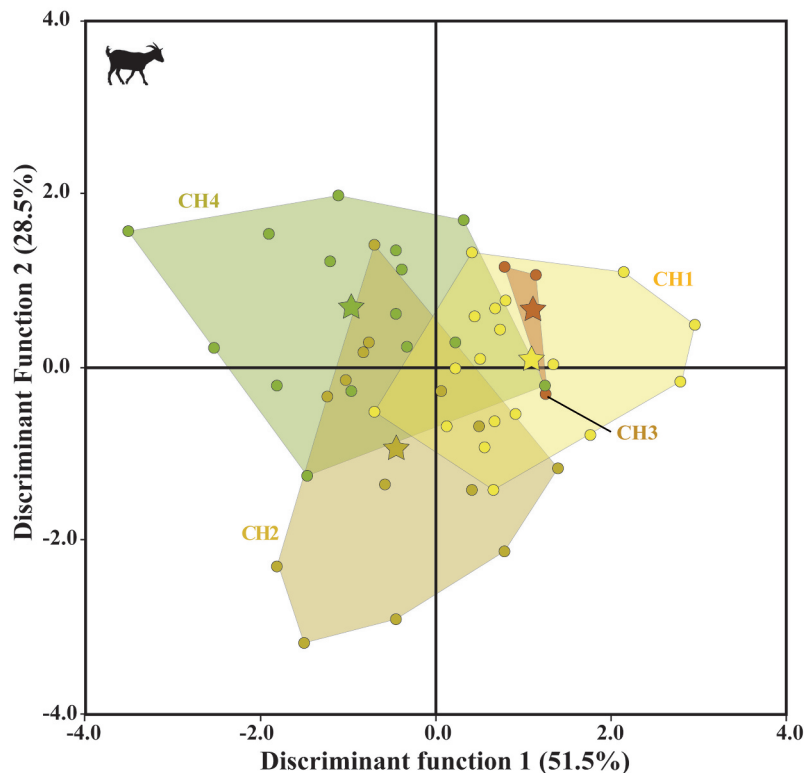
Figure 3. Biplots (mean and standard error of the mean) of complexity (Asfc), anisotropy (epLsar), heterogeneity of complexity (HASfc9) of the four management strategies of domestic goats (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac).

Table 2. Mean (Mn), standard error of the mean (SEM) and standard deviation (SD) values of SSFA textural parameters of wild and domestic extant goats. Asfc: complexity; epLsar: anisotropy; HASfc9: heterogeneity of complexity.

Extant wild and domestic goat groups		<i>C. hircus</i>	<i>C. hircus</i>	<i>C. hircus</i>	<i>C. hircus</i>	<i>Capra ibex</i>	<i>Capra nubiana</i>	<i>Capra pyrenaica</i>
		Laghouat (CH1)	NE Iberian Peninsula (CH2)	Pyrenees (CH3)	Larzac (CH4)	(CI)	(CN)	(CP)
Asfc	Mn	1.14	1.81	2.1	2.6	4.07	3.34	5.0
	SEM	0.17	0.22	0.15	0.54	0.42	0.42	0.53
	SD	0.71	0.87	0.27	2.1	1.47	1.45	2.3
epLsar	Mn	0.00178	0.00181	0.00179	0.00179	0.00178	0.00176	0.00180
	SEM	2.2×10^{-4}	2.2×10^{-4}	4.5×10^{-5}	2.3×10^{-4}	2.5×10^{-4}	1.7×10^{-4}	1.7×10^{-4}
	SD	9.2×10^{-4}	8.9×10^{-5}	7.9×10^{-5}	8.8×10^{-4}	8.6×10^{-4}	6.1×10^{-4}	7.5×10^{-4}
HASfc9	Mn	0.48	0.68	0.35	0.49	0.59	1.0	1.14
	SEM	0.048	0.074	0.061	0.09	0.081	0.17	0.21
	SD	0.19	0.29	0.1	0.34	0.28	0.57	0.93

Table 3. Classification of extant domestic specimens using the classificatory rule obtained from a Quadratic Discriminant Analysis (QDA).

Extant domestic goat groups	<i>C. hircus</i> Laghouat (CH1)	<i>C. hircus</i> NE Iberian Peninsula (CH2)	<i>C. hircus</i> Pyrenees (CH3)	<i>C. hircus</i> Larzac (CH4)
<i>C. hircus</i> Laghouat (CH1)	13 (72.2%)	2 (11.1%)	3 (16.7%)	-
<i>C. hircus</i> NE Iberian Peninsula (CH2)	1 (6.7%)	11 (73.3%)	1 (6.7%)	2 (13.3%)
<i>C. hircus</i> Pyrenees (CH3)	-	-	3 (100%)	-
<i>C. hircus</i> Larzac (CH4)	1 (6.7%)	2 (13.3%)	1 (6.7%)	11 (73.3%)

**Figure 4.** Quadratic discriminant analysis of ISO parameters of domestic modern goats. The star represents the mean for each group (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac).

wild goats from the Near East (CN) were the best classified (100% and 83.3% respectively). In contrast, domestic goats managed in the Laghouat steppe (61.1%) and in overgrazed areas (66.7%) were more poorly classified (Table 3).

The goat groups occupied different areas of the QDA texture-dietary plot (Discriminant Function 1 = 42%, Discriminant Function 2 = 18.2%), some of them overlapping each other (Figure 6). Overall, the mean of the four domestic groups presented negative values along axis 1 (excepting CH3), while the three ibex groups had positive values. Goats managed in the Laghouat steppe and overgrazed areas presented the lowest values. According to the discriminant coefficients (Table S1.4), specimens with negative values showed less rough dental texture surface than individuals that plot in positive values. The ibexes generally had more positive values than domestic goats,

suggesting a rougher and more complex surfaces. Among the wild goats, the ibexes from the southern Iberian Peninsula displayed the roughest dental surface compared to the other groups.

Differentiation of dietary regimes using ISO bivariate graphs

According to the Tukey's post-hoc analysis based on ISO 25178 (Table S1.5), the variables with the most significant differences across the four main categories of ISO parameters (height, function, volume and feature) were selected. There are Spk (function), Sq (height), Vmp (volume) and Spc (feature). Subsequently, they were combined in six bivariate graphs (Figure 7).

Domestic goats had low values for height (Sq), volume (Vmp), function (Spc) and feature (Spk), indicating more flattened dental

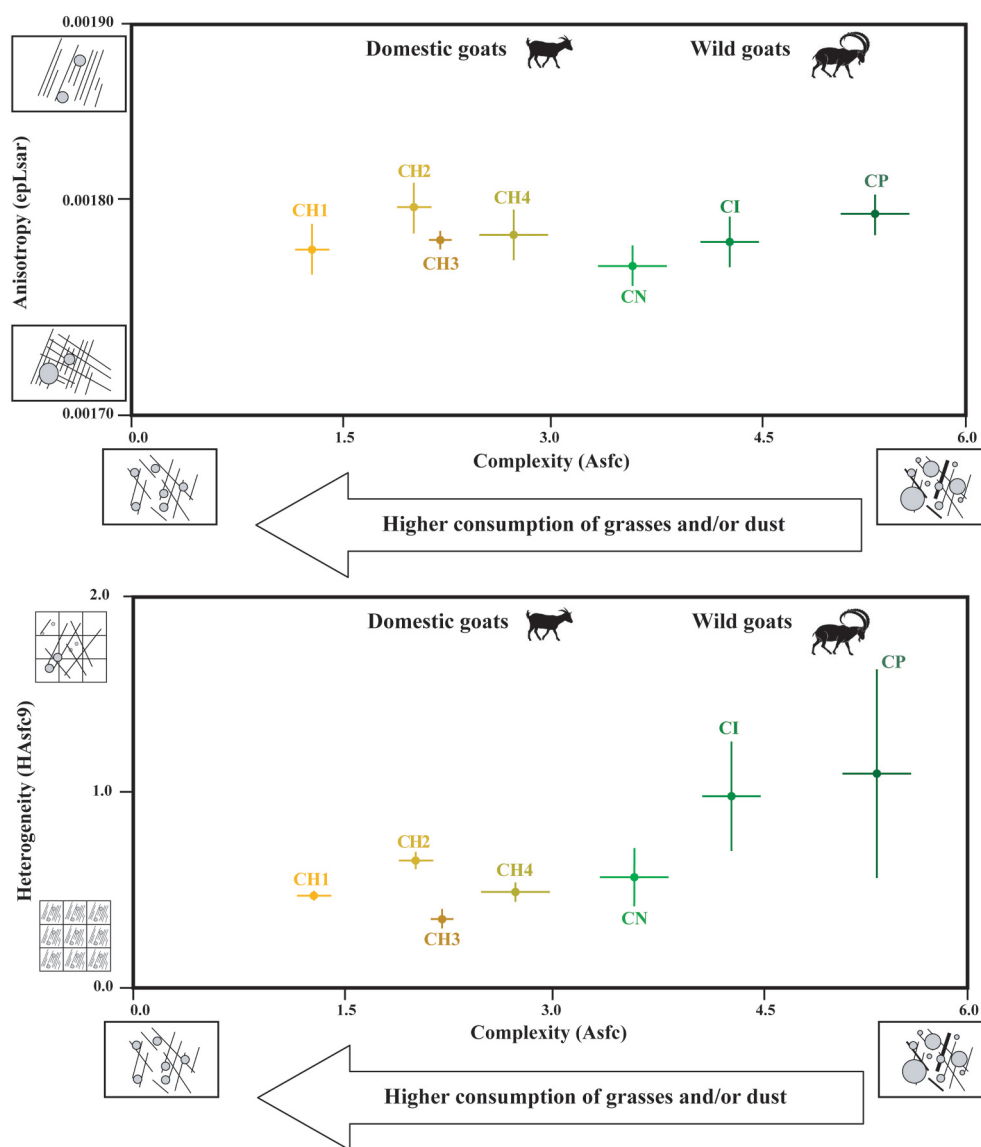


Figure 5. Biplots (mean and standard error of the mean) of Complexity (Asfc), anisotropy (epLsar), heterogeneity of complexity (HASfc9) of the four management strategies of domestic goats and wild ibexes (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac; CI= *Capra ibex*; CN= *Capra nubiana*; CP= *Capra pyrenaica*).

texture surfaces than those of wild goats. Among the four groups of domestic goats, those managed in Laghouat (CH1) had the lowest values for all four parameters. In contrast, goats that grazed in wooded areas (CH4) showed higher values than the previous ones. Goats managed in grasslands (CH3) and overgrazed areas (CH2) showed intermediate values. These data indicate that the higher intake of ligneous plants increases the values of height, volume, feature and function. Among the three groups of wild ibexes, CP showed the highest values for all four parameters. Excepting for Spc parameter, CN displayed the lowest ones, and CI intermediate values.

Archaeological application

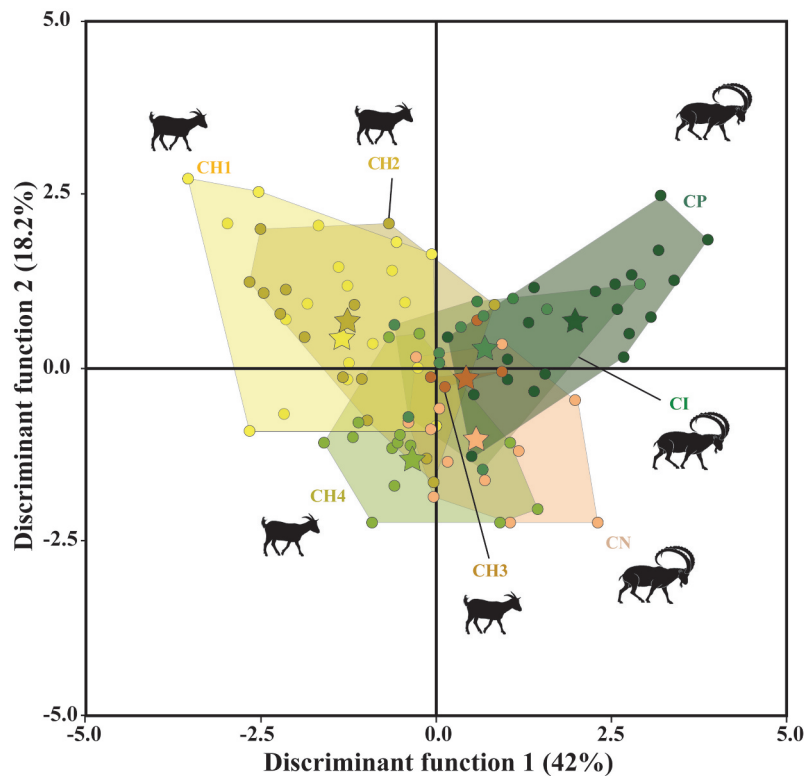
SSFA parameters (Asfc, epLsar and HASfc9) were extracted from the archaeological specimens of Tell Qarassa ($n = 3$) and Kharaysin

($n = 13$) (Table 5). The obtained values were incorporated into the reference database (Figure 8). In terms of complexity (Asfc), the archaeological goat values are very close to those of the domestic goats with a more diverse diet (CH4) and those fed on grasses (CH3). Heterogeneity values (HASfc9) are higher compared to the domestic groups and closer to the wild ibexes, particularly to CP and CN. As for anisotropy (epLsar), the values from Kharaysin resemble those of both domestic and wild goats. However, it is worth noting that the values of Qarassa are much lower than any of the modern goats studied.

Subsequently, the archaeological specimens were incorporated into the QDA obtained from the reference collections of modern wild and domestic goats (Figure 9). Among the goats from Qarassa, one exhibits negative values for DF1, another displays positive values, and the third one shows intermediate values. Regarding the goats from Kharaysin, the specimens showed a high degree of variability. Specifically, three individuals have negative values for

Table 4. Classification of extant wild and domestic specimens using the classificatory rule obtained from a Quadratic Discriminant Analysis (QDA).

Extant wild and domestic goat groups	<i>C. hircus</i> Laghouat (CH1)	<i>C. hircus</i> NE Iberian Peninsula (CH2)	<i>C. hircus</i> Pyrenees (CH3)	<i>C. hircus</i> Larzac (CH4)	<i>Capra ibex</i> (CI)	<i>Capra nubiana</i> (CN)	<i>Capra pyrenaica</i> (CP)
<i>C. hircus</i> Laghouat (CH1)	11 (61.1%)	3 (16.7%)	3 (16.7%)	-	1 (5.6%)	-	-
<i>C. hircus</i> NE Iberian Peninsula (CH2)	1 (6.7%)	10 (66.7%)	1 (6.7%)	-	2 (13.3%)	1 (6.7%)	-
<i>C. hircus</i> Pyrenees (CH3)	-	-	3 (100%)	-	-	-	-
<i>C. hircus</i> Larzac (CH4)	1 (6.7%)	-	-	11 (73.3%)	2 (13.3%)	1 (6.7%)	-
<i>Capra ibex</i> (CI)	-	-	-	-	11 (91.7%)	-	1 (8.3%)
<i>Capra nubiana</i> (CN)	-	1 (8.3%)	1 (8.3%)	-	-	10 (83.3%)	-
<i>Capra pyrenaica</i> (CP)	-	-	4 (21.1%)	1 (5.3%)	2 (10.5%)	-	12 (63.2%)

**Figure 6.** Quadratic discriminant analysis of ISO parameters of domestic and wild extant goats. The star represents the mean for each group (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac; CI= *Capra ibex*; CN= *Capra nubiana*; CP= *Capra pyrenaica*).

DF1, another three displayed positive values, and the remaining seven plot near '0'.

The predictive model obtained for the four domestic goat groups and the three wild goat species using the QDA was used to classify the archaeological specimens (Table 6). 58.3% of individuals from Kharaysin were classified within one of the wild goat groups. Specifically, four individuals were classified with dental abrasions comparable as those of *Capra nubiana* (CN), and three were classified as *Capra ibex* (CI), indicating a mixed diet with tendency to grasses (see 2.1.5 and 2.1.6). 41.7% of

individuals were classified within the domestic groups. Among these, three showed a diversified diet similar to CH4, two have tooth abrasions comparable to those found in goats that fed in wooded and overgrazed areas (CH2), and one was classified as goats fed in steppe (CH1). Concerning the archaeological specimens from Qarassa, two individuals were each classified within a different wild species group (i.e. *Capra nubiana* and *Capra ibex*), and only one within one domestic goat group. Specifically, it was classified within the group of domestic goats that fed in mixed vegetation (CH4).

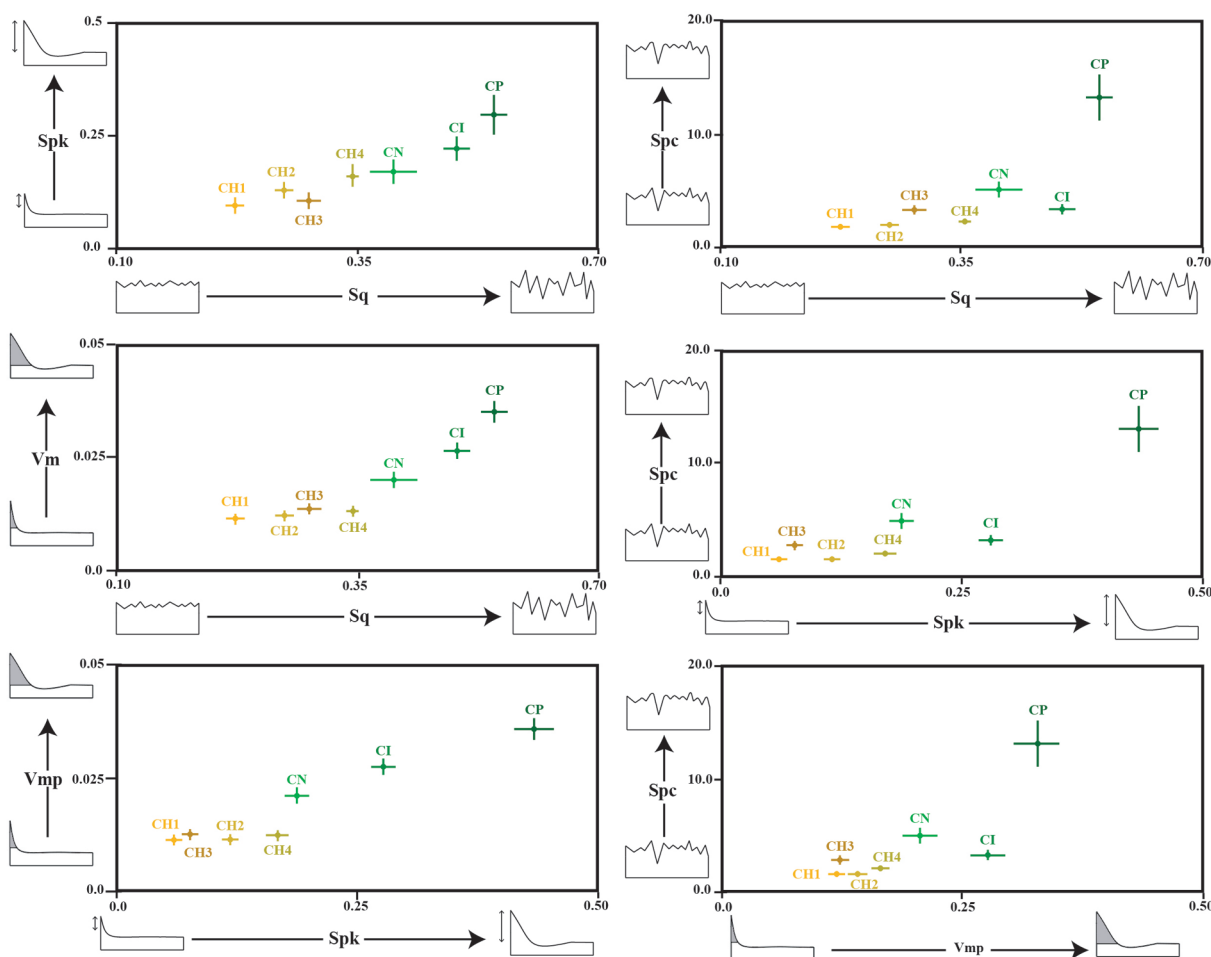


Figure 7. Biplots of the mean five most discriminant ISO parameters of domestic and wild extant goats and their respective standard errors (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac; CI= *Capra ibex*; CN= *Capra nubiana*; CP= *Capra pyrenaica*).

Table 5. Mean (Mn), standard error of the mean (SEM) and standard deviation (SD) values of SSFA textural parameters of archaeological specimens from Tell Qarassa and Kharaysin. Asfc: complexity; ePLsar: anisotropy; HAsfc9: heterogeneity of complexity.

Archaeological specimens		Kharaysin	Tell Qarassa
Asfc	Mn	2.45	2.63
	SEM	0.33	0.26
	SD	1.19	0.45
ePLsar	Mn	0.0179	0.0172
	SEM	4 ($\times 10^{-4}$)	6 ($\times 10^{-4}$)
	SD	1.4 ($\times 10^{-3}$)	1 ($\times 10^{-3}$)
HAsfc9	Mn	0.87	1.31
	SEM	0.27	0.38
	SD	0.97	0.7

Discussion

This study presents the dental microwear texture analysis of 51 domestic goats and 43 wild ibexes. Domestic goats came from four different localities and were managed differently with contrasted grassland-woodland intakes; and the wild ibexes came from three geographical areas where they fed on the vegetation available in their environments. In this work, we explored whether, and how, DMTA can discriminate these modern goat groups. For this purpose, we combined SSFA and ISO parameters, which allow a correct differentiation among diet groups (Ackermans et al. 2020). This work represents the largest database of domestic ungulates,

excluding controlled feeding experiments, for palaeodiet reconstruction using DMTA.

Discrimination of domestic goats

The results presented in this work demonstrate that tooth wear textures vary according to management strategies. Domestic goats fed in the Laghouat steppes (CH1) showed the lowest values for complexity (Asfc), height (e.g. Sq) and volume (e.g. Vmp), and presented the roundest and smallest peaks (Spc and Spk). This degree of dental abrasion can be explained by their high consumption of grass plants, rich in phytoliths (see section 2.1.1). These results are consistent with previous works, which have shown that a diet composed of monocot plants (e.g. grasses) generates low values of complexity and a less rough dental texture wear (Scott et al. 2005, 2006, 2012; Ungar et al. 2012; Merceron et al. 2016; Ramdarshan et al. 2016; Francisco et al. 2018). In addition, the Laghouat steppe is an arid environment (e.g. Belala et al. 2018) and, consequently, goats potentially consumed high proportions of dust and/or grit. The presence of small exogenous particles in the diet can lead to less complex and less rough surface (e.g. Ramdarshan et al. 2016; Merceron et al. 2016; Winkler et al. 2020; Ackermans et al. 2020; Louail et al. 2022). Therefore, goats herding in environments such as the steppe without supplies of fodder, where grasses and dust/grit consumption is important, display

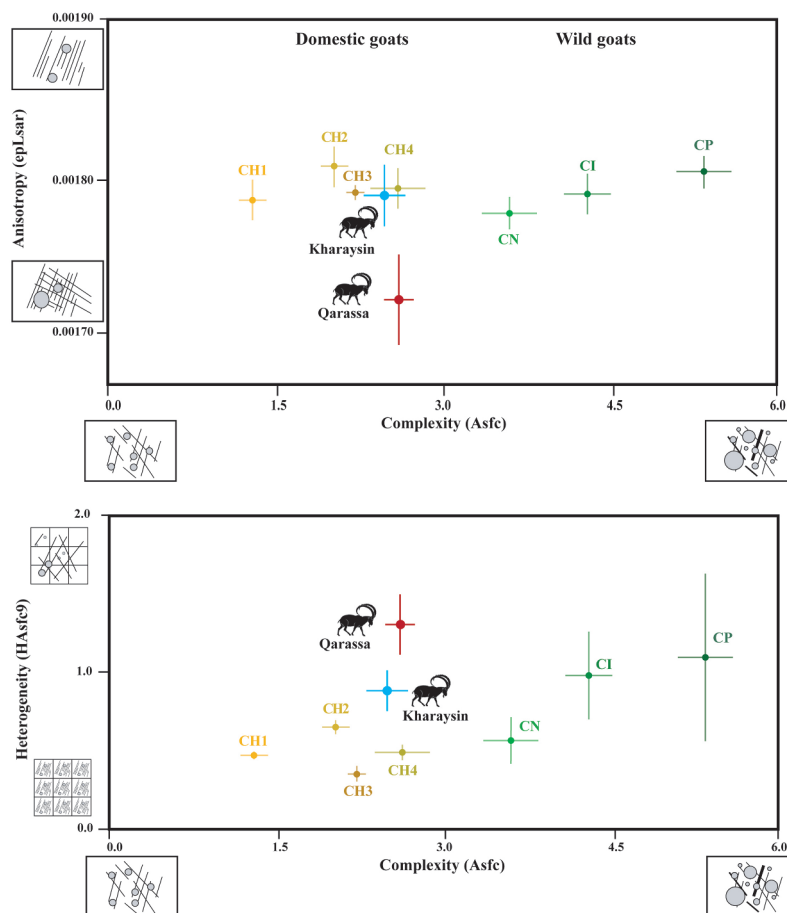


Figure 8. Biplots (mean and standard error of the mean) of Complexity (Asfc), anisotropy (epLsar), heterogeneity of complexity (HASfc9) of the four management strategies of domestic goats, wild ibexes and archaeological specimens from Kharaysin and Qarassa (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac; CI= *Capra ibex*; CN= *Capra nubiana*; CP= *Capra pyrenaica*).

dental wear with very little roughness and complexity, and rather a flattened surface.

The groups of domestic goats grazing in an overgrazed environment (CH2) and grassland areas (CH3) also exhibited relatively low values for complexity, volume and roughness, although higher than those of the previous group of domestic goats (CH1). The differences observed between goats fed in Laghouat steppe (CH1) and those in grasslands and overgrazed areas (CH2 and CH3) can be attributed to the higher loads of dust and grit in the steppe environment. Another explanation can be the variation in the degree of humidity among different vegetation types. The limited moisture content of plants in the Laghouat steppe may lead to a more abrasive dental microwear pattern (Winkler et al. 2021). In contrast, domestic goats from the Pyrenees (CH3) and the northeastern Iberian Peninsula (CH2) were managed in pastures with higher humidity levels. There is not available reference collection with animals fed with dry and wet food. However, despite the difference in the materials analysed, a texture analysis of lithic 3D use-wear conducted on a reference collection revealed that harvesting dry cereals generated more abrasive use-wear compared to wet cereals (Ibáñez et al. 2021). Future research could encompass domestic caprines managed pastures with different degrees of humidity to explore the potential impact of this factor on DMTA.

Goats managed in the Causse of Larzac (CH4) had a mixed diet consisting of monocotyledonous and eudicotyledonous plants. This is thus the group of domestic goats which ingested the highest

proportion of eudicotyledonous plants among the groups analysed in this work. Their diet resulted in a tooth wear more complex and rougher than the other domestic goat groups. These results are coherent with previous works that attested that the intake of eudicotyledone herbaceous plants (clover fodder) causes dental wear rougher and more complex (e.g. Merceron et al., 2016).

Nevertheless, caution must be exercised as the sample size of CH3 is reduced. In addition, our results have some limitations since DMA can vary according to the season, sex and age (Merceron et al. 2010; Rivals et al. 2015; Berlioz et al. 2017; Uzunidis, 2020; Jiménez-Manchón et al. 2023). In this study, these factors could not be considered because they were not available for most specimens. Future research will need to consider them to improve our understanding of the effect of these factors on DMTA.

Discrimination of wild and domestic goats

Dental texture microwear patterns of three wild goat populations (*C. pyrenaica*, *C. ibex* and *C. nubiana*) have been compared to those of four management strategies of domestic goats. The results obtained by SSFA and ISO parameters indicate that the three wild goat groups had a dental texture that was more complex (Asfc), rougher (height and functional ISO parameters such as Sq and Sk) and with more volume (e.g. Vmp) compared to the four domestic goat groups. In a previous work (Jiménez-Manchón et al. 2023), the texture dental wear of these three wild goat populations was

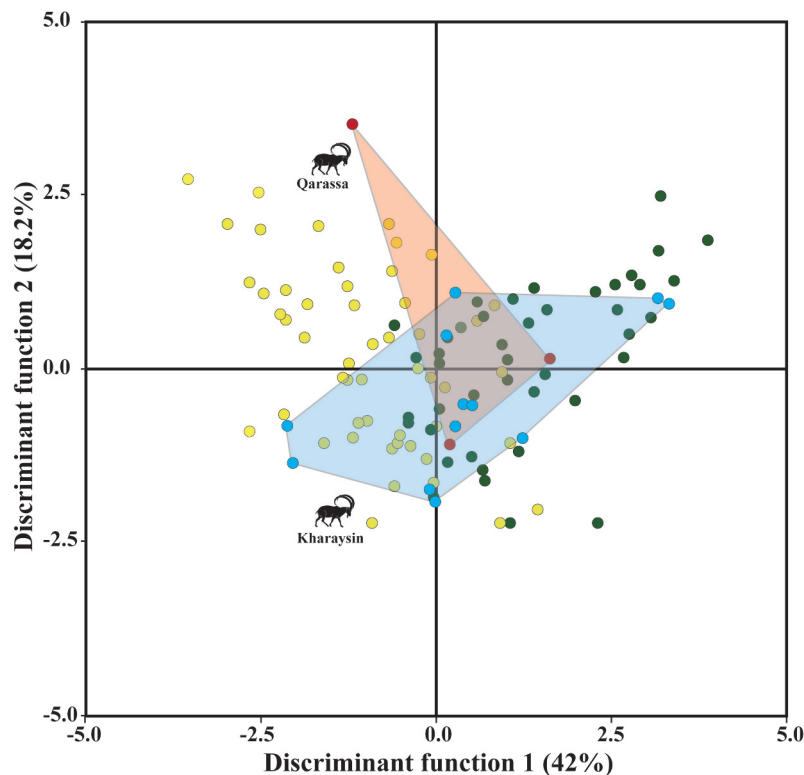


Figure 9. Quadratic discriminant analysis based on modern domestic (yellow) and wild goats (green), and archaeological specimens from Kharaysin (blue) and Qarassa (red) (CH1= goats managed in the Algerian steppe; CH2= in wooded and overgrazed areas in the northeastern Iberian Peninsula; CH3= in grasslands in the Pyrenees; CH4= in wooded areas in the Larzac; CI= *Capra ibex*; CN= *Capra nubiana*; CP= *Capra pyrenaica*).

Table 6. Classification of each archaeological specimen using the classificatory rule obtained from a Quadratic Discriminant Analysis (QDA).

Site	Specimen number	<i>C. hircus</i> Laghouat (CH1)	<i>C. hircus</i> NE Iberian Peninsula (CH2)	<i>C. hircus</i> Pyrenees (CH3)	<i>C. hircus</i> Larzac (CH4)	<i>Capra ibex</i> (CI)	<i>Capra nubiana</i> (CN)	<i>Capra pyrenaica</i> (CP)
Kharaysin	2	0.00030	0.00002	0.00000	0.00210	0.00000	0.99758	0.00000
Kharaysin	3	0.00000	0.00000	0.00000	0.00000	0.99199	0.00801	0.00000
Kharaysin	6	0.00172	0.00228	0.00000	0.00885	0.00044	0.98671	0.00000
Kharaysin	8	0.00000	0.00826	0.00000	0.40708	0.00022	0.58444	0.00000
Kharaysin	10	0.00000	0.00000	0.00000	0.00063	0.14181	0.85756	0.00000
Kharaysin	13	0.00526	0.76544	0.00000	0.12377	0.10287	0.00266	0.00000
Kharaysin	18	0.00022	0.09758	0.00000	0.60940	0.00738	0.28543	0.00000
Kharaysin	19	0.00317	0.05347	0.00000	0.86631	0.00064	0.07640	0.00000
Kharaysin	22	0.00003	0.08134	0.00000	0.31768	0.55854	0.04242	0.00000
Kharaysin	25	0.72611	0.00405	0.00000	0.26821	0.00000	0.00164	0.00000
Kharaysin	29	0.00000	0.06856	0.00000	0.07686	0.74698	0.10760	0.00000
Kharaysin	32	0.00078	0.00587	0.00000	0.77161	0.00000	0.22174	0.00000
Kharaysin	33	0.13323	0.81376	0.00000	0.04946	0.00310	0.00046	0.00000
Qarassa	10	0.00001	0.13667	0.00000	0.76480	0.04058	0.05794	0.00000
Qarassa	17	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000
Qarassa	25	0.00000	0.00007	0.00000	0.00173	0.97515	0.02306	0.00000

compared to that of the domestic goat group fed in an overgrazed environment in the northeastern Iberian Peninsula (CH2). The preliminary results of this previous work indicated a more abraded tooth texture surface in domestic goats than in wild ibexes. In the present paper, the inclusion of three management strategies (i.e. CH1, CH3 and CH4) supports the results obtained by our previous study (Jiménez-Manchón et al. 2023). These differences can be explained by the higher consumption of woody plants by wild goats (see sections 2.1.5 to 2.1.7) compared to domestic goats.

A dental microwear texture dominated by pits and scratches of different sizes tends to produce more complex surfaces (Ungar et al., 2007). In this sense, Asfc values for wild ibexes are more

variable than in domestic goats (Figure 5), suggesting the consumption of both hard and soft plants. Other hypotheses, including mechanical and physiological factors, can also explain that (Jiménez-Manchón et al. 2023). Domestic goats would have taken more small abrasive particles and/or soft food than wild goats. Domestic goats were fed in human-made environments and, therefore, the availability of grasses and the intake of dust/grit were probably higher. However, other factors can contribute to these differences between wild and domestic caprines. Physiological factors, such as the difference in muscle force, may play a role in this (e.g. Harbers et al. 2020; Neaux et al. 2022). The possible differences between rumination processes between wild and domestic caprines

(García-González 1987; Cuartas and García-González 1992; Clauss et al. 2006) could also explain that since it affects DMA (Hatt et al. 2019, 2020). Dust and grit are washed off by the liquid of rumen and this process varies according to the diet, the sex of animals and between ruminants (Clauss et al. 2009).

The higher variability found in wild goats compared to domestic goats could be explained by the fact that the mobility of wild taxa is not controlled by humans. Consequently, the resources available in their diet are more diverse than in domestic goats. Other factors that could contribute to this high variability may include differences in feeding behaviours between males and females in extant ibex populations (e.g. Cuartas et al. 1996), as well as seasonal variations. Considering that DMTA reflects the last food intakes before death, seasonality can influence the results (e.g. Merceron et al., 2021). In future work, other techniques, such as dental cementum, could be employed to address this issue (Naji et al. 2022; Jiménez-Manchón et al. 2023). In regard to variability among wild goats, *Capra nubiana* (CN) exhibits lower values for complexity (Asfc), height (e.g. Sq) and volume (e.g. Vm) when compared to *Capra pyrenaica* (CP) and *Capra ibex* (CI). CN is the only studied species that inhabits a dry environment (i.e. desert). This can be attributed to the substantial intake of dust and grit, resulting in a more abrasive dental wear. Moreover, different degrees of humidity within plants, as previously suggested in the case of domestic goats (see 4.1), may provide an additional explanation.

It is worth mentioning the similarities between dental microwear texture between the domestic group with a rougher and more complex dental texture wear, CH4, i.e. herding goats in mixed vegetation in southern France, and the Nubian ibexes (CN). Nubian goats were fed in an arid environment and, therefore, it is the species with the highest grass consumption among the wild populations studied in this work and the availability of resources in their environment is lower than for the other wild goat species (i.e. CP and CI). Even so, the dental microwear pattern was rougher and more complex than those of domestic goats.

Our results show a gradient in dental microwear texture based on the intake of grasses, dust/grit, and woody plants among domestic goats fed on Laghout steppes (CH1), domestic goats with a mixed dietary regime (CH4), Nubian goats with a significant intake of grass plants and the wild ibex from the southern Iberian Peninsula (CP) and the Alps (CI).

Exploring the use of ISO 25,178 parameters

In DMTA, Scale-Sensitive Fractal Analysis (SSFA) is broadly used for the analysis of ungulate and primate palaeodiet reconstructions (e.g. Krueger, 2015; Martínez-Martínez et al., 2022). The main variables are: complexity (Asfc), anisotropy (epLsar), heterogeneity of complexity (HAsfc) and textural fill volume (Tfv). These parameters can be easily presented in bivariate or univariate plots because of the low number of variables.

More recently, researchers have extended the use of ISO 25178 parameters. These parameters are used for animal diet reconstruction, but also in lithic use-wear (e.g. Ibáñez et al. 2019). These variables are powerful because they can measure orientation of micro-features, anisotropy, height, volume and area at the same time for a given sample using confocal microscopy. Due to the high number of parameters (>30 parameters), statistical procedures to reduce the number of parameters have been proposed in several works (Francisco et al. 2018; Ackermans et al. 2021), with the aim to ease visualisation of the results. In this work, we explored the visualisation of the ISO 25178 in bivariate plots, as proposed in previous works (Ackermans et al. 2020). For this purpose, a post-

hoc pairwise analysis was performed. We selected the most discriminant variables of four parameter groups: Vmp (material volume of the core at given material ratio, for volume), Sq (root mean square height, for height), Spc (arithmetic mean peak curvature, for feature) and Spk (peak reduced height, for function). Previous works have already demonstrated the effectiveness of these parameters to discriminate animal diets. Purnell et al. (2013) and Ibáñez et al. (2020) attested that the consumption of woody plants increases the volume (Vmp) of the texture of dental wear. Winkler et al. (2020) observed that Spc can be used to discriminate diets according to the size and shape of the particles consumed. Finally, Sq is a parameter broadly used to distinguish rough and flattened surfaces in DMTA (e.g. Yamada et al. 2018; Francisco et al. 2018; Louail et al. 2022).

The results presented in bivariate plots in Figure 7 are very consistent with those obtained by SSFA (Figures 3 and 5) and by discriminant analysis (Figures 4 and 6). The goat group with higher intake of ligneous plants presented high values for volume (Vmp), height (Sq), peaks (Spk) and pointed-shaped peaks (Spc). More specifically, among domestic goats, those fed in the Laghout steppe presented the lowest values for these four parameters. In contrast, goats fed in mixed areas presented the highest ones. The same trend was observed with wild goats. They presented higher values for these parameters than the domestic ones. Among wild ibexes, *C. pyrenaica* had the highest values, and *C. nubiana* the lowest. These bivariate plots, although they could also be presented in univariate plots, could be an easier alternative to visualise the different diets in goats using ISO 25178 parameters.

Reconstructing goat palaeodiet in the neolithic near east

Several zooarchaeological findings support the early goat management in the southern Levant since Early Pre-Pottery Neolithic B (c. 8500–8100 cal. BCE) and Middle Pre-Pottery Neolithic B (c. 8100–7500 cal. BCE) periods (Horwitz et al., 1999; Munro et al., 2018; Gourichon and Horwitz, 2021). However, determining the status of goats (i.e. wild or domestic) in this region is challenging due to difficulties in morphological distinction. To address this issue, palaeodiet reconstruction is a powerful approach, as dietary behavioural changes may have occurred before morphometric differences emerged. In this sense, a previous study demonstrated the potential of DMTA to tackle this matter (Jiménez-Manchón et al. 2023). Moreover, this technique allows the exploration of feeding strategies, pasture types (e.g. woodland or open areas), and foddering practices during the Early Neolithic period. In the aforementioned work (Jiménez-Manchón et al. 2023), palaeodiet reconstruction was carried out on archaeological goats from the early Neolithic sites of Tell Qarassa and Kharaysin. This investigation utilised a comparative reference collection of wild goats (*Capra nubiana*, *Capra ibex* and *Capra pyrenaica*) alongside a single management strategy in domestic goats (extensive grazing on wooded and overgrazed areas).

In this paper, we analysed the same individuals from these two sites using a broader comparative database (i.e. three wild species and four management strategies). The results obtained in this study show that half of the archaeological goat specimens from Kharaysin are classified in one of the wild goat groups, specifically *C. nubiana* and *C. ibex*, while the other half fall into one of the groups of domestic goats. The results are coherent with the previous work (Jiménez-Manchón et al. 2023), suggesting the occurrence of animal husbandry control during Middle Pre-Pottery Neolithic B at this site. Additionally, it is important to note the high variability found in Kharaysin, which may again indicate the coexistence of

both domestic and wild goats (Jiménez-Manchón et al. 2023). The inclusion of a large number of management strategies in this paper allowed us to refine the type of management strategy. Archaeological goats are predominantly classified in the CH4 group, indicating that they fed in mixed vegetation (eudicots and grass plants). These results could indicate that these goats could have grazed in the surrounding of the site, which were dominated by wooded steppe vegetation, with a prevalence of eudicots such as *Quercus* and *Pistacia*, as well as grasses (e.g. Asouti et al. 2015).

Regarding Tell Qarassa, two individuals were classified as wild ibex (*C. nubiana* and *C. ibex*) and one was classified within one of the groups of domestic goats. As for Kharaysin, this specimen was classified in the CH4 groups, indicating a mixed diet consisting of eudicots and grass plants, as found in the surroundings of the site (Arranz-Otaegui et al., 2017). Notably, for the goats from Tell Qarassa, high values of heterogeneity (HAsfc9) and low values of anisotropy (epLsar) are observed. These values could indicate a heterogeneous wear pattern across the dental surface, suggesting high variability in diet and predominant consumption of eudicot plants (Scott et al. 2012; Merceron et al. 2016). However, these interpretations should be taken with caution due to the reduced number of specimens studied.

The application of this new comparative reference collection demonstrates the potential of DMTA to characterise palaeodiet in domestic and wild ungulates in Archaeology, enabling the exploration of broader topics such as feeding strategies employed by herders, as well as more specific issues, such as differences in feeding behaviours between wild and domestic ungulates. In future research, additional feeding strategies, such as types of fodder, will be incorporated to the database.

Conclusion

The palaeodiet reconstruction of domestic ungulates is a valuable source of information on livestock management, as it is possible to assess the food management, the foddering strategies and landscape use in late Prehistory. Dental microwear analysis is a non-destructive powerful approach for palaeodiet reconstruction. Unlike wild ungulates, the number of works dealing with the analysis of palaeodiet in domestic mammals is still scarce. These works have been mainly carried out using low-magnification dental microwear analysis (LMDA) and the discrimination of palaeodiets, i.e. browsers and grazers, of domestic animals with this technique is not well adapted. A previous work showed that the use of texture quantitative analysis (DMTA) allows better discrimination in domestic ungulates than LMDA (Ibáñez et al. 2020).

In this paper, we built a reference collection of modern domestic goats with different exploitations and diets using DMTA. More precisely, we analysed goats fed in the Laghouat steppe, on grasslands of the southern side of the Pyrenees, in wooded and overgrazed areas of the northeastern Iberian Peninsula, and in wooded areas of the Causse of Larzac in southern France. This study shows that it is possible to discriminate quantitatively different dietary regimes through DMTA.

The groups of modern domestic goats presented a texture dental wear linked to the type of pasture and diet. Thus, the group of domestic goats with a higher intake of grasses and dust/grit (goats fed in the Laghouat steppe) presented a less complex and very abraded texture dental wear. In contrast, the group with a more diversified diet (goats fed in wooded areas in the Causse

of Larzac in southern France) presented a higher roughness and complexity. The two other groups, fed in grasslands and overgrazed areas, presented intermediate values. The comparison between the tooth wear of these domestic goat groups and three wild goat populations shows significant differences. Domestic goats generally present a more abraded and less complex dental wear than that of wild ibexes. Our data support the results obtained in previous work (Jiménez-Manchón et al. 2023). These differences could be explained by mechanical factors, i.e. a higher intake of soft food and small abrasive particles by domestic goats, although physiological and behavioural differences between domestic and wild goats cannot be ruled out, especially because the study deals with four different species (one domestic and three wild). Additionally, we explored the reduction of ISO 25178 parameters to easily visualise the results obtained by this type of parameter. Our results indicate that the most discriminant parameters are Vmp, Sq, Spc and Spk. These variables can be used to discriminate among goat palaeodiets using bivariate and/or univariate graphs. This comparative reference collection comprises wild and domestic goats and was used to characterise the palaeodiet of archaeological goats from two Pre-Pottery Neolithic sites in the southern Levant, namely Tell Qarassa and Kharaysin. The results reinforce those obtained in a previous study (Jiménez-Manchón et al. 2023), suggesting human feeding control for part of the goats. In this paper, the incorporation of additional management strategies suggests that early managed goats in the southern Levant were potentially fed in a mixed environment dominated by wooded plants.

This paper demonstrates the potential of DMTA to differentiate wild and goat populations and to discriminate various management strategies. However, it is important to note that this database does not encompass all the diversity that exists currently or might have existed in the past. This is particularly evident in the fact that a few of the archaeological specimens studied fall outside the reference models (domestic and wild) used (Figure 8). Furthermore, caution must be exercised as the modern specimens were collected in different seasons, potentially affecting sample variability. Other factors to consider include sex, much of which was unknown in modern specimen databases. Additionally, sample size has to be considered, which is limited in some modern goat populations and archaeological assemblages. Future research will incorporate bioarchaeological approaches to address these issues, such as cementum analyses, new wild goat species, management strategies, and archaeological data to further enhance our understanding of the impacts of known diets in DMTA for palaeodiet reconstruction in Archaeology and Palaeontology.

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