

BIODIVERSITY CONSERVATION FROM THE PERSPECTIVE OF DIET COMPOSITION OF THE DOMESTIC GOAT (*CAPRA HIRCUS*) ON SOCOTRA ISLAND (YEMEN) - WHAT GOAT'S EXCREMENTS CAN REVEAL ABOUT THE LANDSCAPE

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ABSTRACT

Goats are known as some of the most impactful invasive mammals on islands and are now considered the sixth greatest threat to plant communities worldwide due to uncontrolled and extensive grazing. The negative impact of the growing population of semi-feral animals on endemic plants in Socotra Island (Yemen) is well known. Yet, there is virtually no data on the proportion of individual endangered plant species in the diet of goats. It is also unknown whether and to what extent goats consume non-native plants, and what factors influence the overall composition of their diet. This study is the first to focus on the dietary habits of domestic goats on the island of Socotra using DNA barcoding of plant remains in goat excrements. We hypothesize that goats browse on woody plants, including tree seedlings, mainly during the dry season, as in the rainy season, there are sufficient grass and herbs. Therefore, the dry season is crucial for the survival of woody plant seedlings, when high mortality of saplings is not caused only by drought but also by overgrazing. Our results are consistent with this hypothesis. We found a statistically significant positive correlation between the dry season and woody plants grazing and a negative correlation between altitude and grazing of endemics. The reduction of goat's abundance on the island is a necessary management measure to ensure the tree protection and their regeneration, which should be accompanied by a change of goat grazing system and active support of tree regeneration.

Keywords: overgrazing, tree regeneration, non-native species, barcoding, Socotra

INTRODUCTION

Domestic goats are a significant invasive mammal species on islands, with a proven negative impact on native plant communities, leading to a sharp decline or even the

extinction of endemic species (Bellard *et al.*, 2016; Coblentz, 1978). Globally, goats are ranked the sixth most significant threat to biodiversity because of their detrimental impact on vegetation and landscape integrity (Bellard *et al.*, 2016). Feral goats (*Capra hircus*) rank among the most ecologically damaging invasive species on islands worldwide (Gizicki *et al.*, 2018; Campbell & Donlan, 2005). Their presence results in extensive harm to native habitats, causing significant changes in species composition and disrupting ecosystem functions.

Socotra Island located in the northwestern Indian Ocean belongs to the Republic of Yemen (Habrová & Buček, 2014). The island is particularly significant because of its biological diversity, including the high degree of endemism of local fauna and flora (Autin *et al.*, 2013). In this respect, Socotra is often compared with the Galapagos Islands (Van Damme, 2009).

Modern people inhabited the Socotra Island in late Holocene 6,000 to 3,000 years ago (Černý *et al.*, 2009). On Socotra, goats were probably introduced with the first human immigration waves, at least 2000 years ago, and have become an intrinsic part of the island's natural environment (Scholte *et al.*, 2007). Before their arrival, herbivory could hypothetically have been present in Socotra, although no fossil remains of herbivores have been found so far. Socotra is not a "wilderness" island – but an island that has been shaped by man and his livestock for millennia (Van Damme & Banfield, 2011). The flora is typical of a high proportion of unpalatable, poisonous, spiny species and species that tolerate repeated browsing well.

However, populations of endemic plant species are under enormous pressure from the large population of domestic (semi-feral) goats, which roam freely in all ecosystems from mountain peaks to the capital city (Van Damme & Banfield, 2011). It is almost impossible for woody plants to regenerate naturally, and their populations are often overmatured, leading to increasingly frequent local extinctions (Maděra *et al.*, 2024; Lvončík *et al.*, 2020). In 2019, the population of goats was estimated to be 480,000 animals (Maděra & Van Damme, 2022), which is more than a twenty times higher abundance comparing to the goat population in the sixties (Scholte *et al.*, 2007).

Researchers have verified that dragon tree seedlings (*Dracaena cinnabari*), emblematic of Socotra's biodiversity (Rejžek *et al.*, 2016), face a grave threat, primarily because they cannot withstand goat grazing (Maděra *et al.*, 2019a). Similarly, the survival and development of *Boswellia* seedlings have been severely compromised (Hamdiah *et al.*, 2024) and endemic tree species in the genera *Dracaena* and *Commiphora* have been adversely affected by local overgrazing pressure (Maděra *et al.*, 2019b; La Montagna *et al.*, 2023).

There have been frequent attempts to eradicate goats from islands, yet sometimes with unexpected side effects (Campbell & Donlan, 2005). The eradication of goats on Socotra is not feasible because of their role in providing livelihoods and their cultural significance, with 18 % of the Socotran population having a close affinity with them, considering them as pets (Maděrová *et al.*, 2024). Socotran people exhibits a stronger attachment to goats than many other tropical or subtropical ethnic groups (Maděrová *et al.*, 2024). As noted by Scholte *et al.* (2007), the removal of goats from Socotra would lead to the loss of a crucial element of the island's distinctiveness—its unique combination of endemic plant and animal life, alongside its pastoral customs. Therefore, it is necessary to find ways to optimize goat breeding and protection of endangered species, especially to ensure endemic woody plants regeneration (Maděra *et al.*, 2019a). On the other hand, goat populations can also limit the occurrence of invasive plant species on islands. Invasive plant species are already present in Socotra, albeit not dominant (Kessler, 2002; Irl *et al.*, 2021; Maděra *et al.*, 2013). Goats can also have a potentially positive impact through the practical use of targeted grazing of these species.

Specific data on the preferences of endangered and invasive plant species in the diet of goats, including the influence of the factors that affect them, are still lacking.

Simultaneously, obtaining accurate information about animal consumption is very important in terms of management measures in nature conservation (Thuo *et al.*, 2020). Therefore, the aim of this research was to study food preferences of Socotran goats and to assess the extent of the impact of goats on endangered endemic species with emphasis on woody ones, and their potential role in suppressing invasive plant species.

Our study used the DNA barcoding, one of the more widespread and versatile approaches in studying food composition, commonly used in the study of mammalian feeding ecology, including herbivores (Thuo *et al.*, 2020; Abbas *et al.*, 2011; Palumbo *et al.*, 2021). This involves sequencing target DNA fragments, which are then compared with a database of known sequences to determine the taxonomic origin of the organism under study (Kartzinel *et al.*, 2015).

We hypothesize that Socotran goats browse strongly on woody plants (Fig. 1) including tree seedlings mainly during the dry season, because there are sufficient grass and herbs during the rainy season. The dry season is crucial for woody plants seedlings survival, not only from a drought perspective – the plants on Socotra are well adapted to drought (Nadezhdina *et al.*, 2018), but also from grazing effect point of view.

Fig. 1: Semi-feral goats grazing on mature *Croton socotranus* trees, endemic to Socotra Island (Yemen).



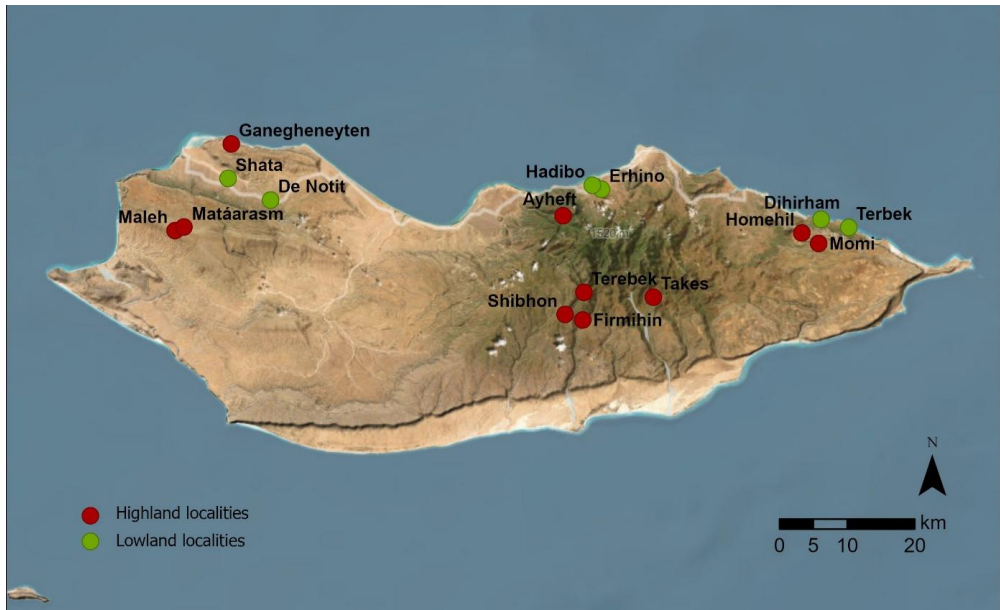
MATERIAL AND METHODS

Study area

The study took place on Socotra Island, located in the northwestern Indian Ocean, between latitudes 12.19° and 12.42° N and longitudes 53.18° and 54.32° E. Socotra spans an area of 3,600 km² (Van Damme & Banfield, 2011). Nearly half of the island's area (48 %) lies below

400 meters above sea level, classified as lowland. The lower highlands, with elevations from 400 to 700 meters, make up 43.5 % of the island's area. The highest point of the island reaches up to 1,535 m a.s.l. (Brown & Mies, 2012). The island's population is approximately 100,000 inhabitants living in more than 300 villages and in Hadibo capital city. The exact population is uncertain due to the lack of a census on Socotra (Maděra & Van Damme, 2022). Socotra's climate is significantly affected by the East African–Indian monsoon system, which features a biannual migrating intertropical convergence zone that moves between its winter position in the northern hemisphere and its summer position in the southern Indian Ocean (Scholte & de Geest, 2010). The monsoon seasons are divided into two: the summer monsoon from May to September and the winter monsoon from October to January (Scholte & De Geest, 2010; Kalivodová *et al.*, 2020). The mean annual rainfall and temperature, recorded at a network of meteorological stations from 2002 to 2006, were 216 mm and 28.9 °C, with high altitudes receiving up to 800 mm (Scholte & De Geest, 2010).

Fig. 2: Map of the villages in Socotra Island (Yemen) where the faecal samples of goats were collected.



Sampling methods

The samples of goat's excrements were collected in 17 villages spread across the entire island (Bezděk *et al.*, 2012) (Fig. 2, Tab. 1). Table 1 offers a detailed overview of the faecal samples collected from goats on the island. Fresh samples from adult female goats were gathered in 2021 (March and November), 2022 (March), and 2024 (November). Although some locations were sampled on all dates, the animals differed as they belonged to separate herds. In total, 446 samples were collected. These samples were sourced from two distinct altitude categories: 201 from lowland regions and 245 from highland areas. The collection included 306 samples from the dry season (March 2021, 2022) and 140 from the rainy season (October 2021, November 2024). This uneven sample distribution across periods reflects unpredictable climate patterns on Socotra Island. During our research, rainy seasons were shorter or absent due to climate-driven changes in precipitation. Rare significant rainfall

reduced the sample collection window, resulting in fewer rainy season samples (n = 140) than dry periods (n = 306).

Table 1: Information on faecal samples collected from goats on Socotra Island, Yemen.

Explanations: a=number of collected samples, b= number of samples without DNA product, c=number of samples with DNA product (in bold), d=number of samples with unreadable DNA product.

Locality	Altitude	March, 2021				October, 2021				March, 2022				October, 2024			
		a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
Shibhon	Highland	40	0	0	0	26	12	11	3	29	5	24	0				
Firmihin	Highland	5	0	0	0					16	2	14	0				
Ayheft	Highland	5	0	0	0	24	10	12	2	21	4	15	2				
Shata	Lowland	39	16	20	3	35	30	5	0	28	24	3	1	10	0	10	0
Erhino	Lowland	11	3	7	1												
Homhil	Highland					15	15	0	0	7	5	2	0				
Taakes	Highland									27	1	6	20				
Momi	Highland									8	1	7	0				
Maaleh	Highland									10	6	4	0				
Matáarasm	Highland									13	9	3	1				
Gangheneyten	Highland									4	3	0	1				
De Notit	Lowland									7	5	1	1	10	7	3	0
Hadibo	Lowland									1	1	0	0				
Terbek	Lowland									19	3	11	5				
Dirham	Lowland									16	6	8	2				
Mona	Lowland													10	0	10	0
Terebek	Highland													10	3	7	0
Total		100	69	27	4	100	67	28	5	206	75	98	33	40	10	30	0
Total highland		50	50	0	0	50	22	23	5	135	36	75	24	10	3	7	0
Total lowland		50	19	27	4	50	45	5	0	71	39	23	9	30	7	23	0

To ensure the samples' freshness, they were collected during morning milking sessions. Using rubber gloves, samples were taken directly from the rectum. Each goat's excrement was placed in a glass vial, with five samples per goat in each vial, and appropriately labelled. The pellets were fixed with 96 % ethanol on-site and kept refrigerated until they could be analysed, as there is no laboratory on the island. Due to the island's high temperatures, often surpassing 30 °C, refrigeration was used to prevent the evaporation of ethanol and potential sample degradation.

DNA extraction and sequencing

The excrements were dried using a freeze dryer Christ Alpha 1-2 (Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany). Lyophilization was carried out for 24 hours at -35 °C and pressure of 0,04 mbar. DNA from feces was extracted from 20 mg of dried material using the DNeasy® Plant Mini Kit (Qiagen, Hilden, Germany) following the manufacturer's instructions. For optimal homogenization of samples the FastPrep® -24 instrument (MP Biomedicals, LLC, Santa Ana, CA, USA) was used.

For analysis of plant DNA in feces the *matK* region of chloroplast DNA was used. A portion of the *matK* gene was amplified using universal DNA barcoding *matK* primers (Jeanson *et al.*, 2011). PCRs were performed using 0.6 units of MyTaq Red DNA polymerase (Bioline, Memphis, Tennessee, U.S.A.) in 15 µl volumes also containing 1× MyTaq Red buffer, 0.2 µMol each primer, and 1 µl of unquantified DNA template. Thermo-cycling was carried out on a Tprofessional basic gradient thermocycler Biometra (Analytik Jena GmbH+Co. KG, Jena, Germany) to the following thermal conditions, initial denaturation at 80 °C for 5 min, followed by 34 cycles of 95 °C for 1 min, 50 °C for 1 min (+ 0,3 °C/s), 65 °C for 4 min, with a final polymerisation step of 65 °C for 5 min. 1 µl of the PCR reaction was checked by agarose electrophoresis. In case of readable PCR products the rest of reaction was purified by FastAP and Exonuclease I enzymes (37 °C for 30 minutes and 85°C for 30 minutes). From 446 samples, only 183 samples provided readable DNA product (Tab. 1)

Purified DNA samples were sent to MacroGen Europe (Amsterdam, Netherlands) for Sanger sequencing. The primers used for amplification were also used for the sequencing reactions.

Data files were assembled and edited using Geneious ® software. Unreadable sequences were discarded from dataset.

Edited DNA sequences were compared with sequences in GenBank via Nucleotide BLAST (NCBI). All sequences are available from the authors.

Plant species identification

Preliminary plant species identification was carried out by comparison with the most similar sequences in GenBank (NCBI). However, because Socotra is an island with a high proportion of endemism, many species have not been included in databases such as GenBank yet. Final plant species identification was conducted by comparison with the Ethnoflora of Socotra (Miller & Moris, 2004).

The following cases appeared:

- 1) Preliminary identified species was in the list of Socotra flora, then it was accepted as the final result.
- 2) Preliminary identified species was not in the list of Socotra flora, but another single species from the same genus occurs, then this species was accepted as the final result.
- 3) Preliminary identified species is not in the list of Socotra flora, but several another species from the same genus occur, then only genus was accepted as the final result.
- 4) Preliminary identified species even genus are not in the list of Socotra flora, then only family was accepted as the final result.

Statistical analysis

Where it was possible, the following traits were assigned to each plant taxon, nativeness (endemic, native and non-native species) and life form (woody plant, herb and grass) using Ethnoflora of Socotra (Miller & Moris, 2004). Not all taxa were possible to assign, for

example *Pulicaria* genus contains more species on Socotra, all of them endemic but *Pulicaria diversifolia* is a widespread herb and other species are shrubs, with *Pulicaria stephanocarpa* being very widespread too. So, it was not possible to estimate which species the sequence belonged to, if the barcoding resulted in only this genus identification. Plant traits were considered dependent variables and environmental factors (altitude and season) independent variables.

Relationships between species composition and environmental factors

Relationships between species composition and environmental gradients were analysed using partial canonical correspondence analysis (pCCA). The analysis was performed on species abundance data, with site identity included as a covariate to account for variation among locations. Permutation tests ($n = 2000$) were restricted within sites to preserve the hierarchical structure of the data.

The interaction between environmental variables (e.g., altitude and weather seasonality) was used as the primary explanatory factor. The resulting ordination axes summarize the main gradients in species composition constrained by these environmental predictors. The direction and magnitude of environmental gradients are represented by black arrows in the ordination diagram.

Species functional traits were passively projected onto the ordination by calculating community-weighted means (CWM) for each site, based on the relative abundances of species. These functional traits are shown as green arrows, allowing visualization of how trait composition aligns with environmental gradients. All ordination analyses were performed using CANOCO software, version 5 (Šmilauer & Lepš, 2014; Ter Brak & Šmilauer, 2012).

Relationships between functional traits and environmental factors

Relationships between species occurrence, functional traits, and environmental variables were analysed using Hierarchical Modelling of Species Communities (HMSC) as implemented in the R package Hmsc (Tikhonov *et al.*, 2020).

The response variable consisted of a species presence–absence matrix (sites $\times$ species), where each row represented a sampling site and each column corresponded to a species. Species occurrences were modelled using a binomial distribution with a probit link function, which is appropriate for modelling species occurrence probabilities. As explanatory variables, the environmental factors altitude (categorical variable) and season (categorical variable) were included in the model as fixed effects, together with their interaction. Functional characteristics of species were incorporated through a functional trait matrix (species $\times$ traits). The traits represented ecological and biological properties of species and included endemism, growth form (woody plants, woody herbs, grasses), biogeographic origin (native vs. non-native), and use as fodder plants. To account for the spatial structure of the data, locality was included as a random effect, allowing the model to capture variation among repeated samples from the same sites and to account for unobserved environmental heterogeneity.

Model parameters were estimated using Bayesian Markov chain Monte Carlo (MCMC) sampling with two independent chains. The MCMC settings included 500 burn-in iterations, which were discarded to allow the model to stabilise and become independent of the starting values. After this initial phase, the simulation was continued and 1,000 posterior samples were retained to characterise the posterior distributions of the model parameters. To reduce autocorrelation among successive samples, only every tenth iteration was stored. Model convergence was assessed by visual inspection of MCMC chains and evaluation of posterior

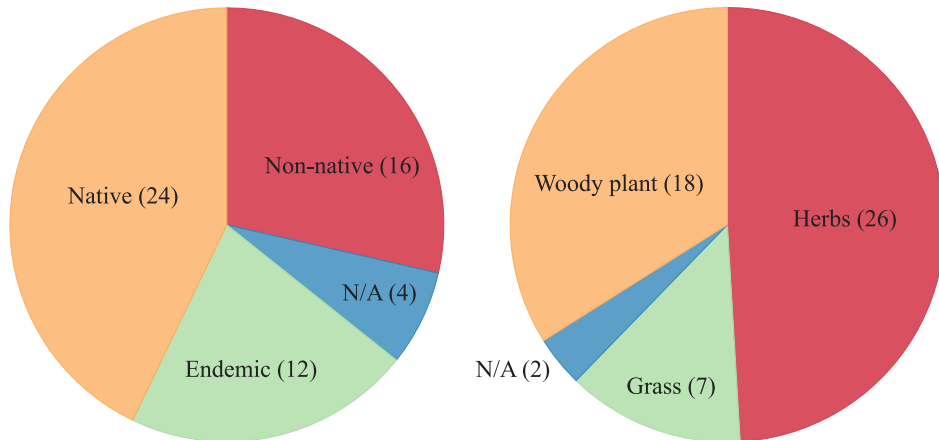
distributions. For each parameter, the posterior probability that the effect was positive was calculated. Effects were considered statistically supported when the posterior probability exceeded 0.95 (or was lower than 0.05 for negative effects). All HMSC analyses were conducted in R (Core Development Team., 2024).

RESULTS

Species spectrum observed

In total, 53 vascular plant taxa have been identified from 183 goat excrement samples in Socotra. Native taxa (including endemic) represented 62.2 % of the sampled spectrum, non-native taxa represented 30.2 %; 4 taxa cannot be assigned containing within the genus/family both native and non-native species (Fig. 3). Similarly, herbs represented 49.1 %, grasses 13.2 % and woody plants 40.0 %, 2 taxa cannot be assigned (Fig. 3).

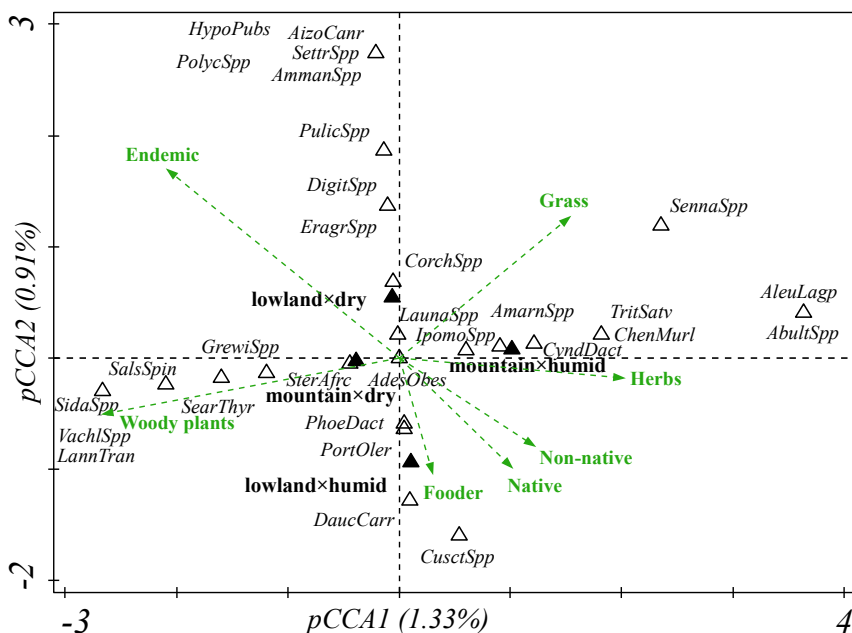
Fig. 3: Number of vascular plant taxa found in goat excrements in Socotra through DNA barcoding with reference to origin (native/non-native) (left) and growth form (right).



At the level of plant species composition, the significant effect on plant representation in the goat diet was observed only in the interaction between season and altitude (pCCA model; permutation test results: on first axis pseudo- $F = 1.1$, $P < 0.001$; on all axes pseudo- $F = 1.8$, $P < 0.001$). The results suggest a possible correlation between the consumption of woody plants and lowland areas during the relatively dry season, or between the consumption of endemic species in the dry season in the lowlands (Fig. 4). In contrast, the consumption of herbs and graminoids appears to be more correlated with the wet season in the mountains (Fig. 4). When explanatory variables were used in the model without interactions, only season had a significant effect. Although altitude and season showed a statistically significant influence on species composition in the goat diet, the explained variation of 2.24 % indicates that the strength of this relationship is weak. Environmental variables thus account for only a small portion of the overall differences in species composition in the goat diet.

Fig. 4: Triplot representing partial Canonical Correspondence Analysis (pCCA) ordination of plant species identified along environmental gradients of altitude and moisture (weather seasonality).

Triangles (Δ) represent species, with their positions reflecting species-environment relationships, while black triangles indicate environmental factors. Green arrows are passively projected to represent the community-weighted mean (CWM) of each functional trait, showing the direction and relative strength of trait associations in the ordination space.



Trends in goat's diet

Endemic taxa and woody plants are more browsed in the dry season while in the rainy season herbs and grasses increased in goat's diet (Fig. 5). These trends are evident regardless of location, whether in the lowlands or in the mountains. In average, the woody plants create 33.3 % of goat's diet at the species composition level, it means from qualitative point of view not quantitative.

Regarding plant traits, a statistically significant negative correlation was found between altitude and the grazing of endemics species, indicating lower consumption of endemics at higher elevations (Fig. 6). In contrast, a strong positive correlation was observed between the dry season and the grazing of woody plants, suggesting increased browsing of woody species during dry periods (Fig. 6). Additionally, the interaction between altitude and season had a significant effect on overall plant trait representation, highlighting that the influence of season on diet composition varies along the elevation gradient (Fig. 6). Trends also suggest that herbs and grasses are more frequently consumed during the wet season in mountainous areas, although these correlations are weaker.

Fig. 5: Representation of individual plant traits (plant nativeness and life forms) within the categories of environmental factors (altitude and season) based on plant identification from goat excrements in Socotra Island (Yemen).

Explanation: Mt=mountains, Low=lowlands, dry=dry season, wet=rainy season.

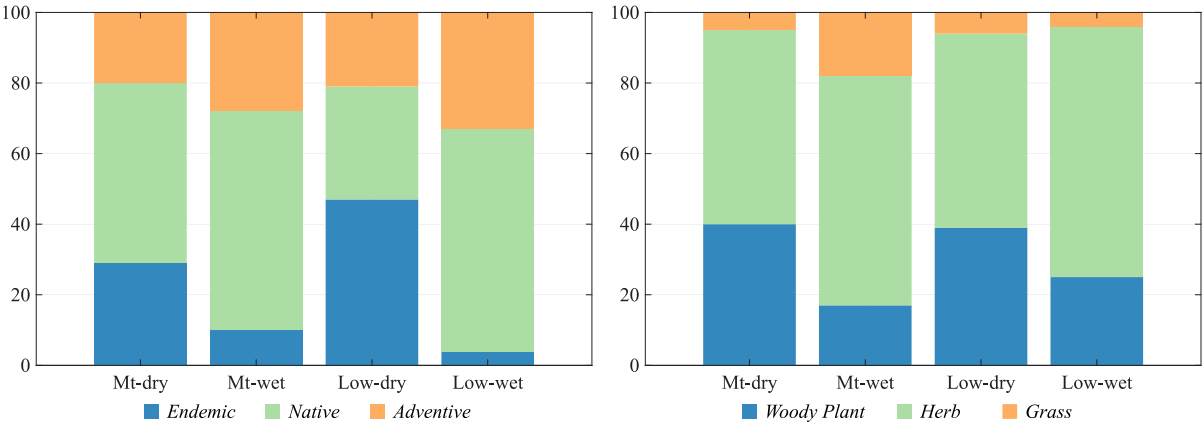


Fig. 6: Heatmap of significant interactions between species functional traits and environmental variables estimated using the HMSC model.

Colours indicate the posterior mean of trait–environment interaction effects, with red representing positive effects and blue representing negative effects, while numbers represent posterior support values. Only effects with posterior support > 0.95 or < 0.05 are shown; non-significant interactions are displayed in white. Positive values indicate positive effects of the environmental variable on the occurrence probability of species with the given trait, whereas negative values indicate negative effects.

0	0.25	0.74	0.6	0.2	0.29	0.17	0.37	Altitude
0.12	0.96	0.33	0.74	0.44	0.66	0.59	0.86	Season dry
0.17	0.33	0.57	0.86	0.92	0.53	0.63	0.59	Season wet
0.10	0.16	0.62	0.64	0.31	0.70	0.25	0.96	Altitude season
Endemic	Woody plant	Herbs	Grass	Native	Non-native	Fodder	Intercept trait	

DISCUSSION

Methodological lessons learned

DNA degradation in faecal samples is a documented problem in nutrition studies. Espunyes *et al.* (2019), who studied the diet of Pyrenean chamois (*Rupicapra pyrenaica pyrenaica*), showed that in excrement left outdoors in winter conditions, the number of plant species detected by PCR-capillary electrophoresis fell from 11 in fresh samples to zero after three weeks. This suggests relatively rapid DNA degradation even in a relatively mild environment.

To minimize degradation, we decided to collect samples directly from the rectum during milking, immediately fixed them in 96% ethanol, and refrigerated them. Despite these measures, only 183 usable DNA products were obtained from 446 samples. Use of metabarcoding instead barcoding could bring higher amount of data from one sample, but the choice of method of analysis was the question of available budget.

Several factors may have contributed to this low success rate. Even though ethanol is a common preservative, prolonged storage or temperature fluctuations during transport may still allow for gradual DNA fragmentation. Although the use of the matK marker offers high taxonomic resolution, it may not always be suitable for degraded DNA due to the relatively long size of the amplicon (typically 700–900 bp).

In studies of primate diets, Bradley *et al.* (2007) addressed similar issues. They noted that PCR amplification of the rbcL and ITS2 regions from the feces of wild gorillas and colobus monkeys often failed or produced sequences that could not be taxonomically distinguished. They improved success by cloning PCR products before sequencing, which could be considered in our future applications. It is also worth considering the possibility of using next-generation sequencing, which would allow for better reconstruction even from degraded samples and, in addition, enable the simultaneous detection of multiple taxa from mixed DNA templates. Despite these advantages, these methods are not accessible to many projects, mainly due to their high cost.

Shepherds on Socotra usually milk only a portion of their goats in the morning, those located near to the village. We took advantage of this opportunity to collect the samples, but by excluding goats grazing far from the village, we may not have obtained all the plant species in the goats' diet, as the flora around the village may have been significantly different compared to more remote areas (Reitalu *et al.*, 2010; Deng *et al.*, 2022). Our results therefore say more about the heavily grazed landscape around villages than about the landscape less affected by grazing. On the other hand, most of the area of Socotra is heavy grazed (Maděra & Van Damme, 2022).

Species composition in goat's diet

The entire surface of Socotra's landscape is literally covered with goat's excrements; it is a proof of strong influence of goats on vegetation of Socotra Island. The Flora of Socotra consists of almost 1,050 species mentioned in scientific literature (Mies, 2001; Schils & Coppejans, 2003; Miller & Morris, 2004; Kilian & Hein, 2006; Cope, 2006; Demissew & Mill, 2009; Raimondo & Domina, 2009; Brown & Mies, 2012; Senan *et al.*, 2012; Řepka *et al.*, 2017; Thulin, 2020; Thulin, 2025a,b; La Montagna *et al.*, 2026), of which more than 250 are considered non-native (naturalised, invasive or only cultivated).

Many species are not palatable or are toxic for goats, many species are very rare or are considered extinct (more than 100 years not seen), so the set of species that could be potentially browsed by goats is much smaller. We recorded 53 taxa, of which 33 are native and 16 non-native (4 taxa could not be assigned, Fig. 3). The ratio is higher in favour of non-native taxa comparing with entire Socotra's flora, that could mean the goats suppress the non-native taxa. Definitely, this topic requires future investigation. On the other hand, currently, many herders are feeding goats by plants cultivated in home gardens, mainly by leaves of date palm. *Phoenix dactylifera* has been recorded 13 times from 183 samples as one of the most frequent species (Fig. 7), of which 8 records were from dry season and 5 from rainy season, predominantly from lowland areas (11 records), which corresponds to the fact that date palms are more frequently planted in lowlands. Not only date palm, but also for example *Daucus carota* has been recorded 6 times from different places of the island or

Triticum sativum (2 times), the feeding of goats with wheat grains is a relatively new practice in recent dry years. Also, the discovery of peanuts (*Arachis* sp.) in one sample and especially marijuana (*Cannabis sativa*) in one sample is quite amusing. These are probably derived from tourists, the local people confirmed, that tourist are smoking marijuana in Socotra quite often. On the other hand, we did not find rice in any of the samples, even though goats are commonly fed leftover rice. This could be because the rice is boiled and the DNA is therefore degraded.

Fig. 7: Date palm leaves have various uses in Socotra, also used as a fodder for goats.



Similarly, the ratio of endemic taxa in our dataset reached 24 % (Fig. 2), which is less than 37 % in entire Socotra's flora (Miller & Morris 2004). Only in the dry season in the lowland the ratio of endemic taxa in goat's diet exceeded 37 % (Fig. 5). As we expected, goats in Socotra graze much more herbs (Fig. 4) and the ratio of endemism is lower than in the woody plants (Miller & Morris, 2004). Surprisingly, only a small ratio of grasses was detected in the goat's diet; 3.5 to 6 % of samples contain grasses and only in the mountains in the rainy season it was higher, up to 16.1 % (Fig. 5). It indicates that grasses have been suppressed by strong long-term grazing of goats in entire island, and where the grasses still occur, the goats do not let them grow up (Fig. 8). The insufficient amount of biomass, especially in dry season, can lead to worse health status of animals. Maděrová *et al.* (2025) mentioned 89 % of goats infected by gastrointestinal parasite and 55.9 % of goats infected with multiple parasites on Socotra Island.

Fig. 8: Fenced areas established for tree re-plantation or as a home gardens clearly demonstrate the productivity potential of land on Socotra and strong grazing effect on grass development. On the left, home garden in Hageher mountains, on the right reforestation area in Homhil.



Effect of grazing on flora and vegetation of Socotra Island

Socotran people have been practised traditional sylvo-pastoral agroforestry system (Maděra *et al.*, 2019a). They use the woodlands for grazing the goats and in dry season, they shake off the leaves and cut the branches from the trees as a fodder for their goats (Miller & Morris 2004). They also use different non-timber forest products, like frankincense (Maděra *et al.*, 2024) or dragon's blood (Al-Okaishi, 2020) or honey as an additional important source of income. From this point of view, the trees are crucial for local traditional land management system and not only from perspective of environmental ecosystem services as for instance Kalivodová *et al.* (2020) mentioned the importance of trees for capturing of horizontal precipitation. As shown in Figs 5 and 6, according to our hypothesis, the goats browse the woody plants in higher intensity during dry season without difference in altitude. As global climate change progresses, we can expect longer dry periods, and therefore the threat to endemic tree species caused by grazing will increase.

This finding has been already supported by many authors. A total of 770,000 trees higher than 5 meters, with an average of 2.14 trees*ha⁻¹, were estimated on the island (Riccardi *et al.*, 2020). Similarly, 480,000 goats are mentioned to be kept by local herders on Socotra (Maděra & Van Damme, 2022) with an average 1.33 goats*ha⁻¹. It means, less than 2 trees are available for one goat in average. These numbers are not sustainable in terms of the use of natural resources. There are many scientific proves documenting tree populations decline on Socotra Island (Habrová *et al.*, 2009; Hubálková, 2011). The flag species of Socotra is endemic and tertiary relic *Dracaena cinnabari*, which suffer of missing regeneration (Maděra *et al.*, 2019b) resulting in unbalanced population age structure (Adolt & Pavliš, 2004; Maděra *et al.*, 2019a) despite germination trials showed very positive results (Adolt & Pavliš, 2004; Baueroová *et al.*, 2020). Also, extreme climatic events like cyclones as a manifestation of global climate change, strongly negatively affect the abundance of population of dragon's blood tree (Vahalík *et al.*, 2023). Very similar situation is in frankincense trees (*Boswellia* spp.), consist of 12 endemic species on Socotra, which is half

of global diversity in this genus. Maděra *et al.* (2024) report a lack of natural regeneration despite good seed germination capability (Hamdiah *et al.*, 2022). Frankincense tree populations were also affected by cyclones hitting Socotra in 2015 (Lvončík *et al.*, 2020).

Many authors agree that the insufficient natural regeneration of woody plants is caused by heavy overgrazing (Adolt & Pavliš, 2004; Attorre *et al.*, 2009; Maděra *et al.*, 2019b; Hamdiah *et al.*, 2024). Woody plants regeneration on Socotra Island is not possible without long-term protection against grazing for instance by fencing (Habrová & Pavliš, 2017). There are two successful examples of tree regeneration using grazing exclosures published by Maděra *et al.* (2019b) for dragon's blood tree using artificial reforestation and by Hamdiah *et al.* (2024) for frankincense trees using natural regeneration. Evidence that the ability of woody plants to regenerate naturally is still vital was provided by La Montagna *et al.* (2025), who investigated the occurrence of woody plants seedlings and offsprings under the protection of unpalatable and thorny nurse shrubs.

Land productivity dynamics during the period 2001–2019 have been studied by Rezende *et al.* (2020) in Socotra Island, using remote sensing data (NDVI). Their results show that over 30 % of the central mountainous areas of the Hageher are decreasing in productivity, whereas in the lowlands productivity has increased significantly, up to 40 % in some areas. These results seem to be somewhat contradictory. Negative changes were recorded mostly in areas with high or medium initial standing biomass while positive in areas mostly with low initial standing biomass. It looks like grazing pressure has shifted from lowlands where is low biomass into higher altitudes during analysed period, but there could be another explanation, in the lowland some unpalatable species gradually spread, like *Tephrosia apollinea*, reported already by Miller & Morris (2004) as very widespread in degraded coastal plains and as an indicator of overgrazing.

CONCLUSIONS

Our study is the first identifying plant remains from semi-feral goat diets in Socotra Island (Yemen), using DNA barcoding. We recorded 53 vascular plant taxa in the goat diets, using the matK gene, of which 33 are native and 16 non-native (4 taxa could not be assigned). Our results, even all analytical limitations and the low rate of explained variations, confirmed the hypothesis that woody plants are browsed by goats stronger during the dry season and that therefore, goats could be a major limiting factor of tree regeneration on Socotra mainly in dry period of the year. The tree populations, and in general the vegetation cover, are in decline (Fig. 9).

Even though our study can be considered as a pilot study and preliminary, the information obtained is of key importance for the future management of goat populations and protection of endemic plant species on Socotra Island. The results could contribute significantly to nature conservation and optimization of goat breeding on the island of Socotra. To improve our knowledge on goat's diet and its effect on vegetation of Socotra Island in future research, we recommend using robust sampling design including also feral goats and for detail species detection we should have a proper established reference sequence database.

From the perspective of sustainable land management, the change of goat breeding habits seems necessary. In light of several studies mentioned above (Adolt & Pavliš, 2004; Attorre *et al.*, 2011; Habrová & Pavliš, 2017; Maděra *et al.*, 2019b; Hamdiah *et al.*, 2024) we recommend first of all, the reduction of goat population is needed. Exclude some area from pastureland and let vegetation to regenerate is second important recommendation. The herb and grass layer regenerate fast (Fig. 8), the land carrying capacity will increase and the pressure of goats on woody plants can decrease. The land enclosure from grazing requests the

change the free grazing system into controlled one. Also feeding the goats in dry season can help to protect tree regeneration, the financial cost of this measure can also help reduce goat numbers. Only complex solutions can help to safeguard endemic tree populations on Socotra; such solutions are important not only from a biodiversity point of view, but also from an ecosystem services point of view, like water capturing from horizontal precipitation.

Fig. 9: Heavily disturbed landscape, overgrazing and significant soil erosion in the highland of Dixam, Socotra Island (Yemen) in the years 2024–2025. The land surface is covered mostly by stones, while trees are almost missing besides some overmature individuals.



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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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