



Livestock displace European mouflon from optimal foraging sites

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Abstract

The conflict between free-ranging livestock and wildlife is a serious conservation concern across rural communities worldwide. Livestock may affect wild herbivores via direct competition for resources due to spatial and diet overlap or via behavioural interference. It is imperative that we disentangle the effects of livestock on wildlife behaviour to obtain an empirical basis able to stir management and conservation decisions. Here, we studied the effect of livestock presence on the habitat selection in a free-ranging European mouflon (*Ovis aries musimon*) population in Sardinia, where the species is under strict protection. We collected spatial data on mouflon and livestock during two consecutive years to investigate whether the mouflon selection of key feeding grassland sites was negatively impacted by the livestock presence. We found that mouflon preferably selected grassland, and its selection significantly increased when grass was of better quality (greener). We showed that livestock presence led to the displacement of mouflon from such preferred feeding sites, an effect clearly exacerbated by livestock proximity. We indeed found that the selection of grassland by mouflon dropped significantly when the distance between livestock and mouflon was below ~650 m, providing a useful management threshold indication. Livestock presence in close proximity displaced mouflon to sub-optimal habitat, and its effects may have negative impact on the population dynamic of this species which is already characterized by low female productivity within harsh Mediterranean environment. Our results give clear management indications aimed at better managing livestock grazing within natural areas to ultimately improve wildlife conservation.

Keywords Domestic ungulates · Competition · Interspecific interaction · Mediterranean habitat · *Ovis aries musimon* · Resource selection

Introduction

Livestock grazing occurs on one-third of the terrestrial ice-free surface (Steinfeld et al. 2006). While ecologists and policy-makers have increasingly recognized livestock farming as an important activity, from both ecological and cultural point of view (Bigmal and McCracken 1992; Thornton 2010), its impacts on wildlife are partly understood and strongly debated (e.g. Saberwal 1996; Mishra and Rawat 1998; Madhusudan 2004; Young et al. 2005). Some authors have suggested that livestock grazing does not affect wildlife (Smith 1992; Prins 2000; Homewood et al. 2001) or even could benefit it (Gordon 1988; Bastian et al. 1991; Vavra and Sheehy 1996), whereas several others have documented negative effects of the introduction of livestock on wildlife (Fleischner 1994; Fritz et al. 1996; Stephens et al. 2001; Mishra et al. 2004). Livestock can have a negative impact on wildlife due to the release of foreign pathogens and parasites (Bengis et al. 2002), increased disease transmission (Gauthier et al. 1992; Woodroffe 1999), increased

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hybridization occurrence (Iacolina et al. 2019), habitat deterioration and reduction (DeMarchi 1973; Westenskow-Wall et al. 1994; Clark et al. 2000), modification of grassland ecosystems (Fleischner 1994), and reduction of forage availability leading to livestock-wildlife conflict (Dunham et al. 2003; Mishra et al. 2004).

Competition over space and shared resources is likely the most important process able to exacerbate the potential impact of livestock on wild ungulates (Prins 2000). Competition between two species occurs in the broad sense if an increase in either one have negative effects on the other (MacArthur 1972). Specifically, two species compete when they both use a resource in short supply or when one species seeking or using the resource harms the other in the process (Birch 1957). Domestic species has often some advantages over wild relatives because their herd densities locally are often far above those of the latter (e.g. Putman 1986; Acevedo et al. 2007; Fankhauser et al. 2008), they are usually led to the best grazing grounds, and they often receive fitness advantage from supplementary feeding and medical attention.

Wildlife may cope with livestock presence by adopting behavioural strategies to avoid or reduce competition and spatial interactions. As a response, wild animals may change their time budget, feeding behaviour, and/or diet selectivity (Putman 1996; Kie 1996; Mattiello et al. 2002; Mori et al. 2020). In most cases, they may change their resource use and move to less favourable grazing sites (Loft et al. 1991; Stewart et al. 2002; Mason et al. 2014; Gaudiano et al. 2021). These behavioural modifications may seem to provide wild animals with the benefit of reduced competition and disturbance; however, they may come at the cost of reduced fitness with consequences on population dynamics (Forsyth and Hickling 1998; Forsyth 2000; Mishra et al. 2004).

A better understanding of the effects of free-ranging livestock on wildlife should be a worldwide priority for conservation management to obtain an empirical basis able to stir decisions promoting a correct coexistence between wildlife and livestock; this is a vital priority in rural areas where livestock breeding is still a dominant economic activity. To fill this gap of knowledge, we collected detailed spatial data on free-ranging livestock and a native ungulate—the European mouflon (*Ovis aries musimon*)—in a remote rural area of Sardinia (Italy). Here, the mouflon is under strict protection by European and local laws, but livestock are often free-ranging even within protected areas where this practice is forbidden but not enforced. The harsh environmental conditions of this Mediterranean area, characterized by scarce and highly seasonal forage availability, can exacerbate competition for best-foraging sites, i.e., grassland. We therefore collected data on grassland quality and built resource selection models to test whether and how livestock presence affects grassland selection by mouflon after accounting for their

quality. We predicted that the access by mouflon to grassland would be negatively affected by the presence of livestock. We hypothesized that this negative effect would increase with decreasing distance to livestock groups and attempted to estimate a useful threshold (if any) indicating a turning point in the effect of the distance of livestock on the likelihood of mouflon to use attractive grassland feeding sites.

Study area

The study was carried out in the centre of Sardinia (Italy, Montes forest: 40°7'N, 9°23'E; Online Resource Fig. S1). The study area (4630 ha, 800–1401 m a.s.l.) is a mountainous area characterized by a Mediterranean climate. The following four habitat categories were recognizable in the Montes forest: oaks (*Quercus ilex*), 444 ha (percentage availability, 16.7%), non-native conifer plantations (*Cedrus atlantica*, *Pinus nigra*, *Pinus pinaster*), 496 ha (18.6%), Mediterranean scrubland (*Arbutus unedo*, *Erica* spp.), 562 ha (21.1%), and grassland mixed with Mediterranean garigue (*Genista corsica*, *Cistus incanus*, *Helichrysum saxatile*, *Rosmarinus insularis*) 1152 ha (43.4%). Autumn census showed that mouflon density varied from 19.3 (in 2005) to 15.7 individuals/km² (in 2007) in the study area, which represents the high-density core area of the species' distribution range. The wild boar (*Sus scrofa meridionalis*) is the only other wild ungulate present in the study site although its presence is low. The only predator of mouflon is the Golden eagle (*Aquila chrysaetos*) that typically preys upon young lambs (Love and Watson 1990). Cattle, goats, sheep, horses, donkeys, and pigs were free-ranging in the study area throughout the years of data collection. Estimated monthly density of livestock in the study areas was 7.7 ± 1.3 cattle/km² (mean ± SE), 6.4 ± 1.5 goats/km², 9.1 ± 1.5 sheep/km², 7.9 ± 1.0 pigs/km², and 0.7 ± 0.2 equids/km² (horses and donkeys). Since 1979 all forms of hunting have been banned in the study area, and mouflon hunting is strictly forbidden everywhere in Sardinia, although poaching is known to be a fairly common practice.

The mouflon occurs nowadays in many populations scattered across Europe as well as in other countries outside Europe (Apollonio et al. 2010). All populations, however, have their roots in the two Tyrrhenian islands of Sardinia and Corsica, where the mouflon was introduced at the beginning of the Neolithic (6000 B.C., Vigne 1992). Mouflon in Sardinia and Corsica is commonly considered as “native through long establishment,” and its populations have been listed in the Annexes II and IV of the Habitat Directive 92/43/CEE. Free-ranging livestock management is still a dominant practice in Sardinia facilitated by both the presence of significant portions of public land devoted to this

activity and large pasture areas cleared by deforestation and fires. Over four million sheep and some hundred thousand of free-ranging cattle, goats, horses, donkeys, and domestic pigs are estimated to be free-ranging in hilly and mountain pastures of the island (Chirichella et al. 2014), which is the environment typically used by mouflon.

Methods

Data collection

We monitored the spatial distribution of mouflon and livestock groups from July 2005 to June 2007. We carried out direct observations along nine fixed transects (length of transects mean \pm S.D.: 5.9 ± 1.2 km; total 47.2 km), proportionally distributed accordingly to the elevation and the habitat categories (i.e. oaks, non-native conifer plantations, Mediterranean scrubland, grassland, and Mediterranean garigue) of the study area. We walked each transects once a month either at dawn or at dusk to locate mouflon when they are active and engage in foraging activity (Pipia et al. 2008) and observed animals by using binoculars from such a distance (at least 100 m) as to minimize disturbance. We walked the transects in close spatial proximity simultaneously to avoid double counts. The presence of a few dozen marked mouflon (ear tagged or collared) allowed us to identify mouflon groups along transects and avoid double counts within the same transect. For each ungulate group observed (either wild or domestic), we recorded the group size and composition, and its location, which was determined by the use of a detailed topographic map (1:1000). Mouflon groups were classified following the categorization proposed by Ciuti et al. (2008): male groups (≥ 2 -year-old males), female groups (≥ 1 -year-old females, lambs, and yearling males), and mixed groups (with at least a ≥ 1 -year-old female and a ≥ 2 -year-old male).

Following Carranza and Valencia (1999), each month of data collection, we measured the grass quality in the main grasslands of the study site where we had randomly selected eight sampling areas. All measurements in each area were made along the same fixed linear transect at five sampling points within 10 m of each other. At each sampling point, in the area of approximately 1 m around it, we dropped a square of 30×30 cm for four times, and we measured the green index and the grass length. The four corner tips of the square touched a leaf blade, which could be either green or brown/yellow. The green index was the number of tips touching green leaves (from 0 to 4) in proportion to the tips touching any blade (0 to 4). In our analysis, we used the monthly mean of green index at sampling points and defined it as grass quality index.

Data analysis

Firstly, we investigated grassland use variation by mouflon as a function of the distance to livestock groups using the presence-only data. We calculated the percentage of mouflon groups observed inside grassland over the total mouflon observations and visualized the variation of grassland use as a function of the distance from livestock groups. We fitted a segmented regression (broken-line model; Benz et al. 2016) to identify the threshold distance at which the effect of livestock on grassland-use by mouflon showed a sudden change. The segmented regression was fitted by using the *segmented* function of the *segmented* package in R, which fitted piecewise linear regression lines with significantly different slopes to subsequent parts of the explanatory variable (Muggeo 2008).

Secondly, to analyse the effect of livestock presence on grassland selection by mouflon, we adopted a “use-availability design” (Manly et al. 2002) and matched locations where mouflon groups were actually observed (hereinafter referred to as “used” locations) to randomly selected locations (hereinafter referred to as “available” locations). We sampled available locations generating independent random points inside nine polygons generated around each line transect, representing the area observable by the operators during data collection (polygon area size: min–max = 57.8–315.1 ha, mean = 167.5 ha). We used a 1:25 use-available ratio that was deemed to be largely enough considering the limited complexity and fragmentation of the habitat in the study area (sensu Ciuti et al. 2018; Brivio et al. 2019). The individual attributes of each mouflon group use location (i.e. group size and composition, date, and time of observation) were also assigned to the corresponding available locations. As we were interested in evaluating grassland selection by mouflon, we classified the different habitat categories of the study area into two main habitat types (i.e. inside grassland/outside grassland). Then, we assigned the habitat type and grass quality index based on spatial coordinates and date of observation for both used and available locations by using QGIS (Qgis 3.4). To evaluate the effect of livestock presence on mouflon selection, we calculated the Euclidean distance to the nearest livestock group observed for each location (used and available) along the corresponding transect, date, and time. Once identified the nearest livestock group, we associated its group dimension. For the locations corresponding to transects and dates without livestock, we assigned as distance from livestock the maximum observable distance, i.e. the maximum width of the transect polygon (minimum–maximum length = 1525–3460 m).

Following the data preparation described above, we built resource selection functions (RSFs) using mouflon group locations. RSF coefficients were estimated by generalized linear mixed model (GLMM) with binary response variable (used = 1, available = 0). GLMM was fitted using the

glmer function of the *lme4* package. We used habitat type (inside grassland/outside grassland), grass quality index, mouflon group type and size, distance from livestock, livestock group size, and Julian date as predictor variables in the model. To account for variation in environmental conditions, we included transect as a random effect in the model. All numerical predictors were scaled $[(x - \text{mean})/SD]$ prior to running the model to improve *glmer* convergence (Bates et al. 2015). The variable screening revealed no collinearity (Pearson coefficient $|r_p| < 0.7$) and multicollinearity (variance inflation factor, $VIF < 3$) among predictors.

We a priori created a GLMM full model structure (inclusive of two-way interactions) based on our expectations of the effect of predictors in driving mouflon grassland selection. We then applied a manual step AIC procedure to remove the interactions and predictors that contributed to the increase of model AIC (i.e. worst model performances). The final RSF was validated using the fivefold cross-validation method developed for presence/available designs by Boyce et al. (2002), which involved calculating the correlation between RSF ranks and area-adjusted frequencies for a withheld subsample of data, that is, 1/5 of the data in a fivefold cross-validation scheme. We investigated the pattern of predicted RSF scores for partitioned testing data (presence-only) against categories of RSF scores (10 bins). A Spearman rank correlation between area-adjusted frequency of cross-validation points within individual bins and the bin rank was calculated for each cross-validated model. Finally, beta coefficients estimated by the most parsimonious model were plugged in the resource selection function to obtain RSF scores, which are proportional to the probability of selection. RSF scores were used to depict scenarios predicted by the model.

Ethics approval

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted. The handling protocols were approved by the Italian National Wildlife Institute.

Results

We observed 512 mouflon groups (group size: mean \pm S.D. = 3.9 ± 3.4) during the two years of data collection, for a total of 1972 individual mouflons. We detected 395 groups of livestock, present in proximity to 152 mouflon groups).

Overall, 46% of used locations by mouflon were inside grassland ($N = 234$). The percentage of locations in grassland was only 12% ($N = 61$) when considering the subset of mouflon observed when livestock were present, even when distant, whereas 34% of mouflon groups ($N = 173$) were inside grassland when considering the subset of mouflon observed when livestock were absent (Fig. 1). The percentage of mouflon groups using grassland increased with increasing distance from livestock. However, this relationship was clearly non-linear. A segment regression analysis identified one inflection point at 655.19 m (Table 1), which represents the threshold distance at which the effect of livestock on grassland use by mouflons changed suddenly. The grassland use by mouflon groups had a steep increase up to

Table 1 Results of the regression model with segmented relationship used to explain the effect of distance on percentage of mouflon groups within grassland observed from 2005 to 2007 in a mountainous region of Sardinia (Italy)

Meaningful coefficients of the linear terms					
	Estimate	Std. error	<i>t</i> value	Pr(> t)	
(Intercept)	-0.482	0.349	-1.381	0.181	
distance	0.016	0.0001	17.938	0.000	
U1.distance	-0.015	0.0001	-16.418		
^a Estimated Break-Point(s):					
	Estimate	SE			
psi1.distance	655.19	23.83			
^b Estimated slopes of the two segments:					
	Est	SE	<i>t</i> value	CI (95%)	CI (95%)
Slope before the breaking point	0.016	0.001	17.938	0.014	0.018
Slope after the breaking point	0.001	0.0001	8.043	0.001	0.001

Results of the most parsimonious broken-line model predicting a breakpoint and two segments, permitting an understanding of the inflection points in distance-related variation in mouflon grassland use

^aPredicted point of inflection is reported

^bSlopes of each of the two segments are reported

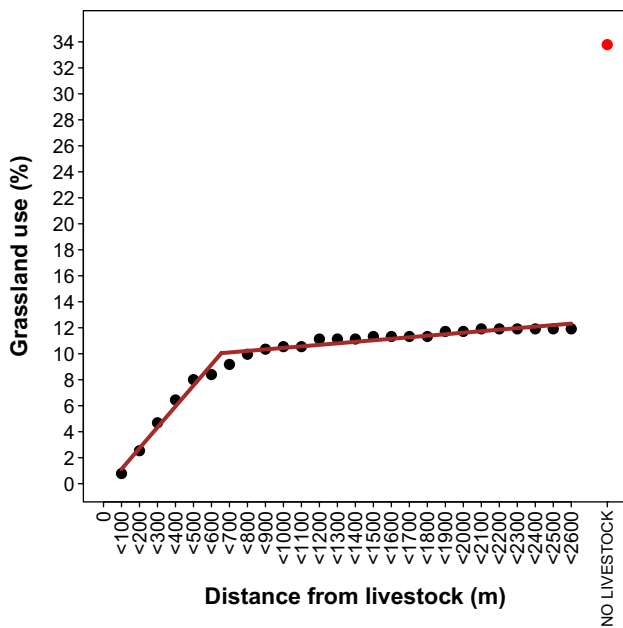


Fig. 1 Percentage of mouflon groups observed inside grassland as a function of distance from livestock groups. Observations were collected from 2005 to 2007 in a mountainous region of Sardinia (Italy). The red point represents the percentage of mouflon groups observed inside grassland when livestock were not present in the monitored sector. The red line represents the regression line as predicted by the broken-line model

this threshold distance, whereas the relationship slightly rose for longer distances (Fig. 1).

In our RSF analysis, we used a total of 13,312 locations, with 25 random locations paired to each mouflon group location. Our starting GLMM a priori model had the following structure:

- (1) Used location (1/0) ~ habitat + GQI + dist + habitat*dist + habitat*mgs + habitat*mgt + habitat*lgs + habitat*J.date + habitat*GQI + GQI*dist + GQI*mgs + GQI*mgt + GQI*J.date + (1|transect) + ε

where “habitat” is the habitat type (inside/outside grassland), “GQI” is the grass quality index, “dist” is the distance to the closest livestock group, “mgs” is mouflon group size, “mgt” is mouflon group type, “lgs” is livestock group size, and “J.date” is the Julian date. We did not include livestock species in RSF because the sample was skewed, having very few observations of sheep, horse, and donkey.

When applying the manual step AIC procedure mouflon group type and size, livestock group size, and Julian date were removed, thus indicating that these variables did not significantly contribute to explain variation in grassland selection by mouflon. According

to the minimum AIC criterion, the most parsimonious RSF model had the following structure:

- (2) Used location (1/0) ~ habitat + GQI + dist + habitat*dist + habitat*GQI + (1|transect) + ε

We found that the model performed quite well when challenged in a fivefold cross-validation ($\rho_{\text{fold1}} = 0.850$, $\rho_{\text{fold2}} = 0.917$, $\rho_{\text{fold3}} = 0.783$, $\rho_{\text{fold4}} = 0.800$, $\rho_{\text{fold5}} = 0.733$, Spearman correlation coefficient $p < 0.001$ in all cases; Online Resource Fig. S2) indicating that the model can properly explain the observed patterns.

Predictions of the most parsimonious RSF model showed that the relative probability of selection for areas inside grassland was higher than that for areas outside grassland (Table 2). Selection for grassland by mouflon was affected by grass quality (significant interaction between grass quality and habitat type), with greater values of relative probability of selection recorded when grass quality index was higher (Fig. 2). On the contrary, selection for areas outside grassland was not affected by the grass quality index (Fig. 2). The interaction between habitat type and distance from livestock groups was also a strong driver of mouflon resource selection. The relative probability of selection for grassland significantly increased with increasing distance from livestock groups (Fig. 3).

Discussion

We showed that livestock presence significantly affected mouflon spatial behaviour, leading mouflon to displace from favourable grassland feeding sites. This negative effect was exacerbated by the livestock proximity: the closer they were, the more likely the mouflons left from the preferred feeding sites. We indeed found that the negative effect of livestock presence became extreme when they were less than 650 m from mouflons. This study clearly showed the impact of livestock on wildlife, and it gives crucial empirical bases in

Table 2 Generalized linear mixed model parameters estimated for the most parsimonious model structure describing habitat selection by mouflon observed from 2005 to 2007 in a mountainous region of Sardinia (Italy). Beta coefficients were extracted and plugged in the exponential resource selection function (RSF) after dropping the intercept, resulting in the resource selection patterns depicted in Figs. 2 and 3

Variable	β	SE	z value	Pr(> z)
(Intercept)	-3.475	0.061	-56.77	<0.001
Habitat type (Inside grassland)	0.697	0.092	7.62	<0.001
Distance	-0.126	0.062	-2.03	0.042
Grass quality index	-0.090	0.062	-1.46	0.145
Habitat type*Distance	0.405	0.092	4.38	<0.001
Habitat type*Grass quality index	0.192	0.092	2.08	0.037

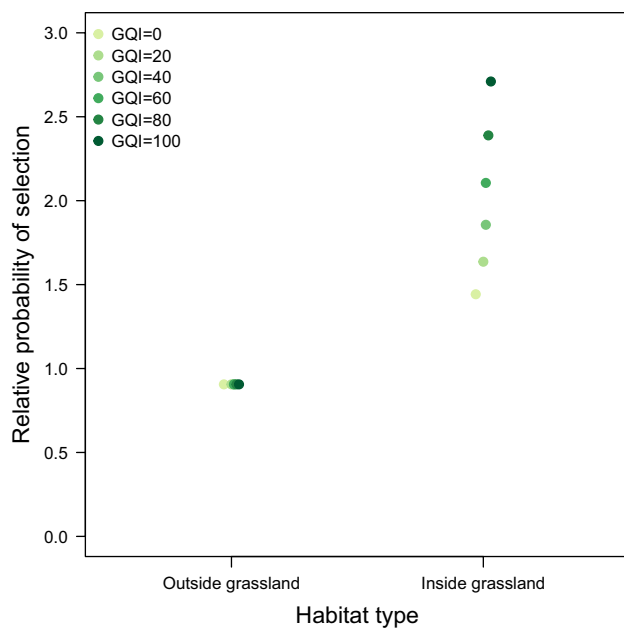


Fig. 2 Relative probability of selection for areas inside and outside grassland in interaction with the grass quality index (GQI) as predicted by the most parsimonious resource selection function, which was built using mouflon observations collected from 2005 to 2007 in a mountainous region of Sardinia (Italy). The data points on the x axis are offset from each other to allow a more comprehensive visualization of results

the understanding of livestock-wildlife conflicts, providing a useful management threshold indication.

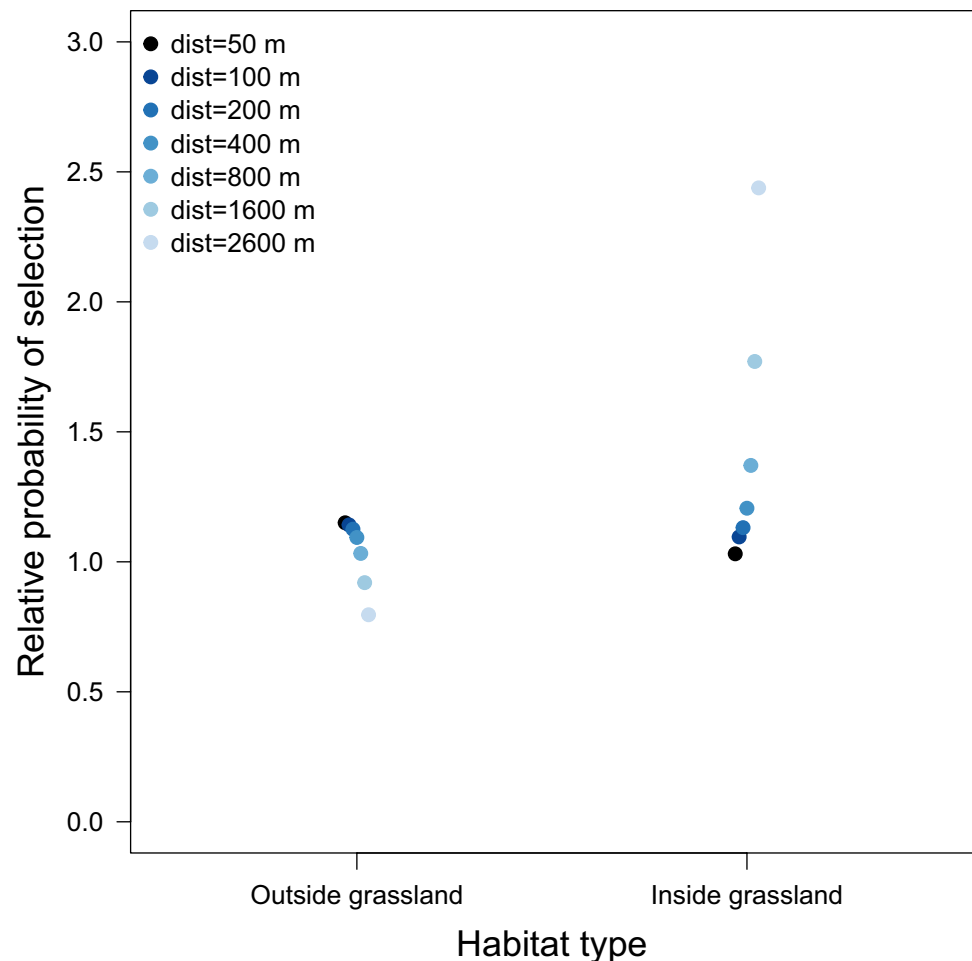
Displacement of native ungulates from preferred feeding sites has been observed by several authors in different ecological conditions (Latham 1999; Borgnia et al. 2008; Chirichella et al. 2013). For instance, in a Mediterranean area in central Spain, the presence of livestock was shown to have a negative effect on Iberian ibex (*Capra pyrenaica*), causing the ibex to select suboptimal areas with poor and sparse vegetation (Acevedo et al. 2007). The spatial displacement is likely to occur because of direct competition, as suggested by different studies on the interaction between wildlife and livestock (e.g. Baldi et al. 2001; Mishra et al. 2004; Madhusudan 2000; Borgnia et al. 2008; La Morgia and Bassano 2009). Alternatively, some authors suggested that behavioural interference may play a role in driving displacement of wild ungulates from livestock grazed areas (Darmon et al. 2014). Livestock presence can cause avoidance behaviour due to direct interaction (e.g. through aggressive behaviours or occupation of the patches; Case and Gilpin 1974; Kronfeld-Schor and Dayan 2003) and visual and audio disturbances, exacerbated by the potential presence of shepherd and guarding dogs (de Leeuw et al. 2001; Bonnington et al. 2007).

In our study area, grassland is the habitat representing the most important food resource for the species (Ciuti et al. 2009). Indeed, mouflon is classified as variable grazer (sensu Gagnon and Chew 2000; Codron et al. 2007), including herbaceous species in a large proportion of its diet (Marchand et al. 2013). Over its wide distributional range, mouflon was found feeding on a wide range of plant species, its dietary diversity reflecting the huge diversity of habitats in which it lives. However, in Mediterranean areas, where the species originally evolved (Rezaei et al. 2010), diet variation was found to be less marked than in other habitats and was shown to be reliant on grasses and shrubs (Marchand et al. 2013). In our study, mouflon showed a preference for grassland and we found that the selection of grassland increased when grass was greener (i.e. higher grass quality index), but also that it is affected by livestock proximity. It is worth noting that the selection probability for areas outside grassland was unaffected by the grass quality index, thus supporting the hypothesis that grassland was selected for its importance in providing high quality food supply.

When livestock were present mouflon decreased the use of grassland, with likely negative consequences on their energy intake. The proportion of mouflon groups observed in grassland was lower (12%) when livestock were simultaneously observed with respect to when livestock were not present (34%). This suggests a displacement of mouflon from grassland as a consequence of livestock avoidance. The inclusion of habitat type interacted with distance from livestock groups in the most parsimonious RSF model further supported this conclusion. The probability of selection for grassland by mouflon increased significantly with decreasing livestock proximity. In accordance, the proportion of mouflon groups observed inside grassland was only 0.8% when livestock were at close distance (< 100 m) and increased when considering observations with livestock at longer distances. The results of broken-line model revealed a threshold distance (i.e. 655 m), under which the negative effect of livestock was particularly strong, leading to a more evident displacement of mouflon from preferred feeding sites.

We revealed that livestock have a negative impact on mouflon resource selection even when present at very long distances. This suggests that mouflon displacement was not simply driven by direct interaction, rather a combination of negative factors was likely involved, including avoidance of areas grazed and deteriorated by livestock (DeMarchi 1973; Westenskow-Wall et al. 1994; Clark et al. 2000), or avoidance of potential foreign pathogens and parasites released by domestic species (Bengis et al. 2002; Gauthier et al. 1992; Woodroffe 1999). Avoidance of human presence associated to livestock groups (shepherd and/or dog) may play a major role in driving mouflon away from the preferred foraging areas. Indeed, some species tend to avoid the human

Fig. 3 Relative probability of selection for areas inside and outside grassland in interaction with distance from livestock (dist) as predicted by the most parsimonious resource selection function, which was built using mouflon observations collected from 2005 to 2007 in a mountainous region of Sardinia (Italy). The data points on the x axis are offset from each other to allow a more comprehensive visualization of results



presence associated with livestock, particularly if they are hunted/poached (e.g. de Leeuw et al. 2001; Bonnington et al. 2007).

Regardless of the actual mechanisms involved in this interspecific interaction, we clearly showed that the livestock presence per se caused displacement of mouflon groups from the favoured grazing sites. The predominant use of sub-optimal areas may strongly limit the possibility of energy acquisition, which may lead to demographic changes in structure and vital rates. Over time, these changes may alter population dynamics, as shown elsewhere where wild ungulates share space with domestic ones (Mishra et al. 2004; Madhusudan 2004). This issue should be of primary interest for conservation biologists because the mouflon populations of Sardinia and Corsica islands are considered as populations of Community importance by the European legislation (92/43/CEE). Moreover, these populations showed one of the lowest productivities among European mouflon populations (Ciuti et al. 2009) suggesting a limited recruitment, possibly due to difficult environmental conditions, including interaction with livestock. It is worth noting that free-range livestock management is still a dominant economic activity

in Sardinia, and it is strictly linked to the rural culture of this island, like many other rural areas around the globe. As the diffusion of free-range livestock is similar in Corsica, the only other island where the mouflon populations are protected by European law, the magnitude of this threat is particularly meaningful in the overall range of this species. Consequently, a special attention not to further decrease the population success through the impacts caused by free-ranging livestock must be paid.

Interference between livestock and native ungulates is a frequent conservation problem around the world, especially in arid environments where food is scarce (e.g. Fritz et al. 1996; Baldi et al. 2001; Mishra et al. 2004). Coexistence can occur; however, native species can suffer a displacement to sub-optimal habitats, as shown in this study. More in general, understanding how wildlife adjust their behaviour to avoid interference with livestock has conservation and management implications (Vázquez 2002), especially because these behavioural modifications could ultimately lead to negative consequences on the population dynamics of wild species (Madhusudan 2004; Mishra et al. 2004).

Management implications

There is a mandatory need for close monitoring of the livestock populations and herding practices to be constantly incorporated into wildlife conservation planning in order to obtain guidelines promoting both correct livestock breeding and the conservation of the mouflon populations. In this respect, our results may help in formulating management guidelines:

- 1) Livestock should be not released on best feeding sites during sensitive periods, such as last stages of pregnancy and weaning, when females need to get access to best feeding sites in order to meet the bigger energetic requirements related to lactation (Clutton-Brock et al. 1989). More in general, livestock presence should be controlled during spring, which is a crucial season for mouflon, as they have to store food reserves in preparation to the hot and dry summer, characterized by food shortage in the Mediterranean areas (Miranda et al. 2012) and by hot thermal conditions which strongly constraint mouflon activity (Pipia et al. 2008; Bourgoïn et al. 2011) and habitat selection (Marchand et al. 2015).
- 2) Our results suggest that there is a threshold distance over which the disturbance effect of livestock tends to decrease. The managers should establish buffer zones where livestock introduction should be avoided in order to ensure the use of sensitive areas (e.g. parturition, mating, water supply areas) by mouflon only, so as to promote a positive coexistence between livestock and mouflon.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s10344-022-01581-y>.

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Author contributions Study conception and design by Simone Ciuti, Anna Pipia, Marco Apollonio and Stefano Grignolio. Data collection was performed by Anna Pipia, Simone Ciuti, and Stefano Grignolio. Data analysis was performed by Francesca Brivio, Simone Ciuti, and Stefano Grignolio. The first draft of the manuscript was written by Francesca Brivio and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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