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RESEARCH PAPER

Numbers and presence of guarding dogs affect wolf and leopard predation on livestock in northeastern Iran

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Abstract

Livestock predation can pose socio-economic impacts on rural livelihoods and is the main cause of retaliatory killings of carnivores in many countries. Therefore, appropriate interventions to reduce livestock predation, lower conflict and promote coexistence are needed. Livestock guarding dogs have been traditionally used to reduce predation, yet details regarding the use of dogs, especially the number of dogs per herd effectively required, are rarely studied. In this study, we assessed how the number and presence of guarding dogs in a herd can reduce livestock losses to leopard and wolf in corrals at night and on grazing grounds in day-time. Using systematic interview surveys (2016-2019), we documented sheep/goat losses per attack (predation rates) from 139 shepherds across 32 villages around Golestan National Park, Iran. We analysed the effects of the number of dogs, presence of dogs, presence of shepherds, seasons, corral quality, livestock number, dog size, distance to villages and distance to reserve on predation rates using generalized linear models. For the leopard model, dog presence significantly decreased ($\beta = -1.80$, 95% confidence interval -2.61 to -0.81) predation rates during day-time to 1.41 individuals per attack. For wolf attacks in corrals at night, predation rates significantly decreased ($\beta = -0.29$, -0.54 to -0.04) with increasing dog numbers. Also, shepherd presence ($\beta = -0.56$, -1.10 to -0.10) and herd size ($\beta = -0.36$, -0.60 to -0.12) significantly reduced predation rates. In the wolf day-time model, shepherd presence significantly decreased ($\beta = -0.93$, -1.74 to -0.10) predation rates. Our study suggests that (1) using dogs can reduce, but not eliminate, predation by leopards during day-time; (2) with every additional dog, predation rates by wolves in corrals at night are likely to decrease on average by 25.2%; and (3) the presence of shepherds in corrals at night and during day-time can reduce predation rates.

Keywords: Carnivore; Evidence-based conservation; Human-wildlife conflict; Iran; Mitigation, Predator

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Introduction

The management of human-carnivore conflict (HCC) remains a contentious issue in many regions of the world (Woodroffe et al., 2007). Predation on livestock is known to be the main source of conflict between large carnivores and humans (Macdonald et al., 2010; Khorozyan et al., 2015). Special characteristics of large carnivores such as their high demand for space and protein-rich diets (Chapron & López-Bao, 2016) drive them to kill livestock or may pose a direct threat to human safety (van Eeden et al., 2017). Particularly, when their habitats are encroached by humans, carnivores have to search widely for more prey and suitable areas inside or near protected areas (Bleyhl et al., 2019; Soofi et al., 2019). Livestock losses can inflict substantial socio-economic costs (Khorozyan, Ghoddousi, Soufi, Soofi, & Waltert, 2020) to local livelihoods and lead to negative attitudes toward carnivore conservation. In response to these threats, local people may kill carnivores in retaliation (Treves & Bruskotter, 2014), which has resulted in local extirpation of many carnivore populations (Treves & Karanth, 2003). Therefore, it is increasingly important to mitigate conflicts between humans and large carnivores to ensure their long-term conservation by facilitating coexistence in shared landscapes (Ritchie et al., 2012; Chapron & López-Bao, 2016).

HCC may occur when wild prey becomes scarcer and carnivores, in turn, switch to livestock (Novaro et al., 2000; Shehzad et al., 2015; Khorozyan et al., 2015; Ghoddousi et al., 2016; Soofi et al., 2019), or when prey abundance is high and carnivores living at higher densities need more food (Suryawanshi et al., 2013). In both of these situations, protection of livestock from carnivores may be required with the application of anti-predator measures or interventions. Interventions can be lethal (killing, trapping and poisoning) and non-lethal (e.g., translocation, sterilization and shock collars) (Breitenmoser et al., 2005; Wielgus & Peebles, 2014; Khorozyan & Waltert, 2019). Use of non-lethal and cost-effective interventions may be able to avoid the social disfavour caused by high financial burdens since costly interventions (translocation, shock collars) can be impractical and ineffective (Treves & Bruskotter, 2014; Khorozyan & Waltert, 2019).

Multiple meta-analyses have summarized information on the effectiveness of evidence-based interventions in reducing HCC (Miller et al., 2016; van Eeden et al., 2017; Khorozyan & Waltert, 2019). A review by van Eeden *et al.* (2017) shows that livestock guarding animals, among multiple management interventions analyzed, were most effective in reducing livestock predation rates by carnivores. By contrast, Khorozyan and Waltert (2019) suggested that fencing and calving control were the most effective measures to mitigate similar losses. Few studies have focused on the effects of the presence of guarding dogs (hereafter referred to as ‘dogs’) on livestock predation rates. For example, Khorozyan *et al*. (2017) in Golestan National Park (GNP), northeastern Iran, found that leopards (*Panthera pardus*) tended to kill more sheep and goats when dogs were absent, but the presence of dogs did not eliminate leopard predation and only reduced surplus killings (i.e. multiple kills within a single attack). Also, a recent study in Mongolia demonstrated that the presence of dogs effectively reduced livestock predation events by wolves (*Canis lupus*) (Leib et al., 2021). A study from France looked at the behavioural interactions between dogs and wolves and suggested that maintaining a certain number of dogs is essential to reduce losses (Landry et al., 2020). However, the effectiveness of the number of dogs per herd in relation to different carnivore species is insufficiently studied. Many factors can influence the effectiveness of traditional husbandry techniques including dogs, corrals or shepherds (Leib et al., 2021). For example, more livestock tend to be killed by carnivores if they are not protected by dogs, corrals and shepherds (Woodroffe et al., 2007; Abade et al., 2014) and if they graze away from villages and close to (or inside) protected areas (Khorozyan et al., 2017).

In this study, we sought to answer the following questions:

1. How are losses of sheep and goats to leopards and wolves affected by the numbers, presence, and size of dogs, corral quality, and distances from kill sites to villages and protected areas?
2. To what extent do the numbers of dogs, presence of shepherds, and the numbers of sheep and goats affect predation rates by leopards and wolves in corrals at night and during day-time on grazing grounds?

Materials and methods

Study area

We conducted our study in 32 villages around Golestan National Park (GNP) located in northeastern Iran (centroid 37.4°N, 56.0°E; Fig. 1). GNP is the oldest Iranian reserve established in 1957, which became a United Nations Educational, Scientific and Cultural Organization (UNESCO) biosphere reserve in 1976 (Darvishsefat, 2006). The park is located in the mountainous terrain and represents a transitional zone between lush Hyrcanian broadleaved forests and dry steppes, with a mean annual precipitation of 142 mm and 866 mm in the east and west, respectively. The park covers an area of 874 km^2 with an elevation range of 450 to 2411 m, and is surrounded by adjoining protected areas such as Zav-1 Protected Area (PA) (50.08 km^2), Zav-2 PA (93.15 km^2), Loveh PA (35.89 km^2) and Azizabad No-Hunting Area (NHA) (207 km^2) (Fig. 1) (Darvishsefat, 2006). According to the International Union for Conservation of Nature (IUCN) protected area categories, GNP belongs to the category II (national park) and PAs to the category V (protected landscape or seascape), while NHAs are temporary (usually for five years) protected areas not formally classified. The forests are dominated by chestnut-leaved oak (*Quercus castaneifolia*), hornbeam (*Carpinus betulus*),

Fig. 1. Distribution of leopard (*Panthera pardus*) and wolf (*Canis lupus*) attacks on sheep and goats around Golestan National Park, Azizabad No-Hunting Area (NHA), Zav-1 Protected Area (PA), Zav-2 PA and Loveh PA from January 2016 to December 2019. Colours other than those on the legend resulted from the overlaps of different colours of the points and the background.

velvet maple (*Acer velutinum*), iron wood (*Parrotia persica*), ash (*Fraxinus excelsior*), Persian holly (*Ilex spinigera*), Christ's thorn (*Paliurus spina-christi*), black hawthorn (*Crataegus pentagyna)* and ferns (e.g., *Dryopteris caucasica*). These forests shift into arid steppes in the eastern part of the park where juniper (*Juniperus excelsa*) woodlands and wormwood (*Artemisia* spp.) scrublands dominate (Akhani, 1998) (Fig. 1). This national park is also home to a variety of native large carnivore species including the globally endangered Persian leopard (*Panthera pardus tulliana*), grey wolf and brown bear (*Ursus arctos*) (Firouz, 2005). The ungulate species including urial (*Ovis vignei*), bezoar goat (*Capra aegagrus*), red deer (*Cervus elaphus maral*), roe deer (*Capreolus capreolus*) and goitered gazelle (*Gazella subgutturosa*) occur mostly inside the park (Soofi et al., 2018), but wild boar (*Sus scrofa*) is widely distributed even on unprotected lands.

Animal husbandry and crop farming are the main activities of local communities around GNP. Most of the villages are located in the forested areas to the west of GNP, with a few more in the steppe and semi-desert zones towards the east (Fig. 1). There are no villages inside GNP and livestock grazing is not permitted in this park, but sometimes it occurs illegally along the park edges (Khorozyan et al., 2017). By contrast, the IUCN category V and IV (habitat or species management area) areas in Iran permit some economic activities, such as livestock grazing, and may contain villages, as is the case with the protected areas near GNP (Darvishsefat, 2006).

Study design

Livestock predation data

We systematically recorded (per shepherd) the number of livestock (namely, sheep and goats, cattle and dogs) killed by carnivores, number of dogs, presence of dogs, presence of shepherd, kill location, carnivore species, number of living livestock, and clues to carnivore identification (e.g., footprint, throat bite, direct observation and carcass laceration) for each carnivore attack from January 2016 to December 2019. We defined the number of livestock individuals in each herd killed per attack as the predation rate. As sheep and goats typically graze together in our study area and have a similar chance to be killed by carnivores (Khorozyan et al., 2017), we combined them in our analysis. This information was collected by Mob.S. through the systematic interview surveys permitted by the Iranian Department of Environment, under the assistance from M.S., both authors are local residents. Interviews were undertaken in two main local languages (Turkmen and Persian) among local shepherds in pastures, farmlands, wild areas, or in their households. If shepherds were not available for in-person interviews, we organized interviews by telephone. We informed the respondents that their cooperation within our study was voluntary and that reports would be used solely for research purposes (Young et al., 2017). We also asked the respondents to inform us as soon as livestock were lost to carnivores. Kill sites were visited directly after the shepherds' reports and the carnivore species were identified on site from species-specific predation signs (Soofi et al., 2019). Local shepherds were familiar with carnivores and sufficiently skilled in distinguishing wolf and leopard signs. We discarded ambiguous predation incidents (Soofi et al., 2019) and used only reliable reports by shepherds. We measured the locations of livestock kills by GPS and visually verified them in Google Earth Pro ver. 7.3 (Google Inc., USA). We measured the straight-line distances between kill sites, closest villages and closest boundaries of protected areas in QGIS version 3.18.1 (QGIS Development Team, 2022).

To assess the efficacy of livestock corrals in reducing livestock predation, we measured the heights of corral walls as the barriers for attacking carnivores. The structure of the corrals may vary (e.g., height, material) at the household level, which influences their overall quality. Therefore, we measured the height of the corral walls (often made of thorny scrubs/reeds, mixed with clay and stone), considering it as a measure of livestock protection (Abade et al., 2014). In addition, we quantified the body size of dogs as 1 for small (body height < 64 cm and body weight < 30 kg), 2 for mid-sized (height = 64−67 cm and body weight = 30−35 kg) and 3 for large dogs (height > 67 cm and body weight > 35 kg). We averaged the size values based on a selected number of dogs kept by each shepherd. We randomly selected three adult dogs for reference, and measured their body weight and their shoulder height from the middle of the backbone along the straightened leg to the tip of the leg (MacNulty et al., 2009). For behavioural reasons (shyness or aggressiveness), direct measurement of all dogs was not feasible; for dogs which could not be measured, shepherds reported their weight and height based on visual recognition according to these criteria.

Statistical analysis

We used generalized linear models (GLM) to model the predation rate for the *i*-th attack (C_i) by each carnivore species as a function of selected predictor variables. The observed count of predation events was modelled as a Poisson random variable. In addition to the Poisson frequency model, we also considered the negative binomial distribution, in which we assumed that the number of observed predation events is a binomial random variable (Soofi et al., 2022). Predictor variables were scaled and checked for multicollinearity using the variance inflation factor (VIF) < 3 (Zuur et al., 2010). We ran three different models: (1) a leopard day-time model (i.e., day and evening kills on grazing grounds), (2) a wolf day-time model (i.e., day and evening time kills on grazing grounds), and (3) a wolf night-time model (i.e., evening and night-time kills inside corrals). We did not have records of leopard attacks in corrals at night.

We applied an information-theoretic approach to select models based on quasi-Akaike's Information Criterion corrected for small sample size ($QAIC_c$) to control for overdispersion (Grueber et al., 2011). For our final inferences, we applied multi-model averaging in the 'MuMIn' package of R (Barton, 2020) and used the best candidate models with $\Delta QAIC_c < 2$ (Grueber et al., 2011). We regarded predictors as significant if their 95% confidence intervals (CI) did not include zero (Soofi et al., 2019). We assume that errors could be modeled as a binomial thinning of the true Poisson frequency. In this case, we expect such biased counts to also be Poisson random variables due to properties of the binomial and Poisson distributions (Dorazio, 2014).

We also used Spearman's rho correlation coefficient to measure the relationship between all the included variables in our models. Finally, we applied one-way ANOVA and Tukey's HSD (honestly significant difference) tests to compare mean differences of wolf predation rates over different numbers of dogs. Lastly, we calculated the proportion of reduction in predation per additional dog using equation:

$$\left(\frac{\widehat{\lambda}_N - \widehat{\lambda}_{N+1}}{\widehat{\lambda}_N}\right) \times 100$$

where N is the number of dogs and $\widehat{\lambda}$ is the estimated predation rate (Fig. 2). All the statistical analyses were performed in R software version 3.6.3 (R Core Team, 2020). We used standard error (SE) as a measure of estimate variation.

Results

We interviewed 139 shepherds across 32 villages around Golestan National Park. We recorded a total of 129 animals killed by leopards, which were mainly sheep (35%, n = 45) and goats (50%, n = 65) compared to dogs (10%, n = 13) and cattle (5%, n = 6). By contrast, wolves, were reported to have killed more often sheep (76%, n = 202) and goats (24%, n = 63). Overall, we recorded 375 sheep and goats killed by leopards and wolves which were more commonly killed by both carnivores than dogs or cattle. Therefore, we analyzed only sheep and goat predation rates. According to the owners' statements, there were 15226 (average per flock = 143 ± 9.99, range = 30−480) sheep and goats and 359 dogs (average = 3.49 ± 0.20) living in our study area.

Leopard predation (sheep and goats)

Our results showed that leopard attacks (47 attacks, n = 75 sheep and goats killed) were only reported during the day-

Fig. 2. The curves showing the estimated declines of sheep and goat predation rates in relation to (A) the dog presence for leopards during day-time grazing, (B) the number of dogs for wolves in corrals at night-time, (C) the presence of shepherds for wolves in corrals at night-time, (D) the number of sheep and goats for wolves in corrals at night-time, and (E) the presence of shepherds for wolves during day-time grazing. The shaded areas represent the 95% confidence interval bands and the black curves show the mean estimates. The dashed lines on the leopard panel (A) indicate the minimum predation rate by leopards in the presence of dogs. On the wolf panel (B), the vertical dashed lines indicate that with every additional dog, predation rates are likely to decrease by 25.2% (24.2−25.9%). The dashed line on the wolf night-time model (C) and the wolf day-time grazing model (E) indicates the minimum predation rates by wolves in the presence of shepherds.

Table 1. The results of model averaging of the best candidate generalized linear models for sheep and goat predation by leopards (*Panthera pardus*) and wolves (*Canis lupus*) in 2016-2019 near Golestan National Park, northeastern Iran. Please see table footnote for explanation of all abbreviations used within the table.

Rank	Model parameters				β-coefficients (standard error)						
	Leopard model (day-time grazing) (P)										
	k	QAICc	Δ	AICw (%)	Intercept	Ndog	DogP	Shoat	Season		Disvil
1	3	123.20	0.00	0.40	3.20 (0.38)	–	−1.80 (0.40)	–	–		–
2	4	124.47	1.27	0.21	3.16 (0.38)	–	−1.76 (0.41)	–	–		−0.13 (0.13)
3	4	124.56	1.36	0.20	3.12 (0.39)	–	−1.71 (0.41)	−0.13 (0.13)	–		–
4	4	124.63	1.43	0.19	2.92 (0.48)	−0.15 (0.16)	−1.48 (0.52)	–	–		–
	Wolf model (corrals at night) (NB)										
	k	QAICc	Δ	AICw (%)	Intercept	Ndog	Corq	Shep	Shoat	Season	Ndog × Corq
1	5	213.20	0.00	0.37	1.18 (0.21)	−0.29 (0.13)	–	−0.56 (0.25)	−0.36 (0.12)	–	–
2	4	215.70	2.50	0.11	1.17 (0.21)	−0.29 (0.13)	−0.01 (0.12)	−0.56 (0.25)	−0.36 (012)	–	–
3	3	215.80	2.61	0.10	1.10 (0.21)	–	–	−0.41(0.24)	−0.43 (0.12)	–	–
	Wolf model (day-time grazing) (P)										
	k	$QAIC_c$	Δ	AIC_w (%)	Intercept	Ndog	Dispa	Disvil	Shoat		Shep
1	3	107.62	0.00	0.42	2.40 (0.38)	–	–	–	–		−0.93 (0.41)
2	4	108.44	0.82	0.27	2.39 (0.38)	–	−0.17 (0.13)	–	–		−0.92 (0.40)
3	4	109.55	1.93	0.16	2.40 (0.38)	–	–	–	−0.10 (0.14)		−0.93 (0.41)
4	4	109.58	1.97	0.15	2.36 (0.39)	–	–	0.09 (0.14)	–		−0.89 (0.41)

Abbreviation of covariates: Corq, corral quality; Dispa, distance from kill site to protected area; Disvil, distance from kill site to village; DogP, presence of dogs; Ndog, number of dogs; NU, not used; Shep, presence of shepherd; Shoat, number of sheep and goats per herd. Abbreviation of parameters: AICw, Akaike's model weight (%); K, number of model parameters; QAICc indicates Quasi−Akaike Information Criterion corrected for small sample size; Δ, difference in QAICc scores between a given model and the best fitting model with Δ = 0 (Burnham and Anderson 2002). P indicates Poisson distribution and NB denotes negative binomial distribution. The line (–) in the table for each model indicates that the particular covariate (s) was not selected by QAIC during model ranking.

time. On average, a leopard killed 1.47 ± 0.18 sheep and goats per attack.

Wolf predation (sheep and goats)

We recorded 41 (n = 67 sheep and goats killed) wolf attacks during grazing in day-time and 57 (n = 147 sheep and goats killed) attacks in corrals at night. On average, wolves killed 1.99 ± 0.21 sheep and goats per attack.

Leopard model (day-time grazing)

In the averaged leopard day-time model (Table 1), only dog presence significantly affected (β = −1.80, CI 95% −2.61 to −0.81) predation rates (Table 1; Fig. 2A). In the absence of dogs, an expected predation rate of sheep and goats was $\widehat{\lambda}$ = 3.17 (CI 95% 2.10 to 4.24) individuals per attack, but when at least one dog accompanied the herd, the expected predation rate decreased to $\widehat{\lambda}$ = 1.41 (CI 95% 1.12 to 1.70) individuals per attack (Fig. 2A).

Wolf model (corrals at night)

In the averaged wolf model (Table 1), an increasing number of dogs negatively affected predation rates (β = −0.29, CI 95% −0.54 to −0.04) (Table 1). This suggests that with every additional dog, predation rates by wolves in corrals at night decreased on average by 25.2% (24.2−25.9%) (Fig. 2B). Our findings from the wolf model further revealed that, on average, 6 dogs were likely to be an effective number of dogs at which wolf predation inside the corrals at night decreased significantly from an expected predation rate of $\widehat{\lambda}$ = 1.49 (CI 95% 1.01 to 2.21) to an expected predation rate of $\widehat{\lambda}$ = 0.35 (CI 95% 0.07 to 1.85) individual sheep and goats (Fig. 2B). A further increase in the number of dogs reduced predation rates by wolves to zero (Fig. 2B). Also, the presence of shepherds in corrals at night significantly affected predation rates (β = −0.56, CI 95% −1.10 to −0.10) (Table 1; Fig. 2C). We also found that an increase in herd size negatively affected wolf predation rates (β = −0.36, CI 95% −0.60 to −0.12) (Table 1; Fig. 2C). Specifically, most predation occurred at night in smaller herds (30−102 sheep and goats), and predation rates were notably reduced when herd sizes were larger (range = 102−480 individuals) (Fig. 2D). Low predation rates by wolves in larger herds was associated with a greater number of dogs in larger herds (*rho* = 0.49).

Wolf model (day-time grazing)

In the averaged wolf day-time model (Table 1), our findings showed that the presence of shepherds in the grazing herds negatively and significantly (β = −0.93, CI 95% −1.74 to −0.10) decreased wolf predation rates from an expected rate of $\widehat{\lambda}$ = 2.41 (CI 95% 1.43 to 3.40) to an expected predation rate of $\widehat{\lambda}$= 1.47 (CI 95% 1.16 to 1.79) animals per attack (Fig. 2E).

Discussion

Human−carnivore conflict is a key driver of population declines of large carnivores around the world (Treves & Karanth, 2003; Woodroffe et al., 2007; Khorozyan & Waltert, 2019). Predation of livestock has been identified as a main factor in many of these conflicts (Khorozyan et al., 2015), which requires management strategies to ensure the long-term conservation of carnivores by promoting coexistence (i.e., co-occurrence of sustainable carnivore populations and human activities with minimal human-carnivore conflicts) in shared landscapes (Venumiére-Lefebvre et al. 2022). In this study, we addressed the effectiveness of dogs in mitigating livestock predation by leopards and wolves around the oldest biosphere reserve in Iran by using systematic interview surveys. We show that both carnivores killed sheep and goats per attack at relatively similar rates, but of the total kills, predation losses to wolves were threefold (71%) more numerous than those of leopards (29%). Such a difference in predation rates might be partially related to the predation strategies of these carnivores (Uboni, Smith, Stahler, & Vucetich, 2017; Soofi et al., 2019). For example, we found no leopard predation in corrals at night, since leopards only predated during day-time on grazing grounds, whereas wolf predation events occurred both in corrals at night (58%) and during day-time grazing (42%).

Our results also showed that leopard attacks were more likely to occur when livestock were not accompanied by livestock guarding dogs, leading leopards to kill more sheep and goats than in attacks when dogs were present. Thus, the presence of dogs still decreased leopard predation risk. Despite livestock being accompanied by dogs, leopards continued to kill sheep and goats, but at lower predation rates (1.41 individuals per attack) compared to occasions when dogs were absent (3.17). These results support results from our previous study in Golestan, which showed that in the absence of dogs, leopards killed more sheep and goats per attack (i.e., 'surplus killing'; Khorozyan et al., 2017). A plausible explanation of these results could be that leopards occasionally tend to kill dogs (n = 12 in our study) for food (Ghoddousi et al., 2016). However, dog killing can be underestimated as leopards are ambush carnivores well adapted to hunt their prey in densely vegetated habitats (Suryawanshi et al., 2013), which may lead to non-detection of killed dogs. This is well supported by the fact that most leopard attacks on sheep and goats occurred in forested areas to the west of Golestan (Fig. 1).

Our results further revealed that wolf predation on sheep and goats in corrals at night decreased by a quarter (25.2%) with every additional dog per predation event. However, we acknowledge that carnivore-livestock relationships can be more complex (Landry et al., 2020) and depend on carnivore ecology (Woodroffe et al., 2007; Abade et al., 2014; Khorozyan & Waltert, 2019). For example, predation rates might increase with an increasing pack size of wolves (Landry et al., 2020), and reduced predation rates likely also depend on behavioural and protective abilities of guarding dogs (Leib et al., 2021). Our findings are also in agreement with the findings of Landry *et al.* (2020) in southern France, who reported that wolf attacks might occur at varying distances (100 m up to 1 km) around the herds and six dogs per herd, coupled with limited segregation of sheep and goat flocks, are required to prevent wolf attacks effectively.

As expected, we found wolf predation rates to be significantly higher in smaller herds kept in corrals at night-time. We surmise that the lower predation rates by wolves on larger herds might have been associated with a higher number of dogs (Landry et al., 2020). Livestock is many times more abundant than wild prey in most localities outside Golestan. Red deer, urial and bezoar goat populations have declined here compared to their population estimates since the 1970s, primarily due to poaching (Ghoddousi et al., 2019) and livestock grazing (Soofi et al., 2018). Distribution of these species is predominantly restricted to the national park and they are extirpated from the neighbouring reserves. Wild boar is the only ungulate that is widespread in Iran, especially in our study area, since it is not hunted by Muslim people for religious reasons (Ghoddousi et al., 2019). Our previous study also confirms that the decline of wild prey abundance due to poaching led to an escalation of livestock predation by wolves and leopards (Soofi et al., 2019).

Our study offers practical insights into strategies for mitigating HCC. There are clear benefits of having an adequate number of guarding dogs per herd to reduce predation rates by wolves at night-time when most (58% in our study) wolf attacks occur. Guarding dogs, however, should be properly trained (van der Weyde et al., 2020; Leib et al., 2021) to function as effective guardians of livestock with minimum lethal encounters with carnivores (Ekernas et al., 2017; Drouilly et al., 2020; Leib et al., 2021) and other wildlife. Apart from being killed by carnivores, on some occasions guarding dogs have been reported to kill carnivores (Nayeri et al., 2021; Leib et al., 2021), and such untrained dogs should not be used in livestock practices. Our study suggests that guarding dogs should always be present around the herd to prevent attacks or at least to reduce surplus killing by carnivores (Khorozyan et al., 2017; Leib et al., 2021; Landry et al., 2020). In line with previous studies, our findings also suggest that keeping dogs has the capacity to reduce predation on sheep and goats by leopards, and having a sufficient number of dogs can be beneficial since we found it nearly eliminated predation by wolves. However, keeping dogs can be costly and therefore depend on the livelihood of the herders (Landry et al., 2020). On the other hand, having dogs might reduce economic impacts of livestock losses on the means of local communities and decrease leopard poaching and lethal control of wolves. Keeping an appropriate number of dogs may also be helpful when compensation payment schemes and other mitigation measures are unavailable to reduce the potential risks of retaliatory killings.

Furthermore, the presence of shepherds may reduce wolf predation rates in corrals at night and on grazing grounds during day-time. For instance, preventing flocks from scattering and grazing them in more aggregated groups can lower predation risk by 1.47 individual sheep and goats per attack, as wolves tend to attack this small livestock in more isolated groups.

Overall, our results suggest that dog presence can reduce, but not eliminate, predation rates on sheep and goats by leopards during day-time. Also, with every additional dog, predation rates by wolves in corrals at night may decrease on average by 25.2%. Finally, provisions to protect livestock could address differences in day-time and night-time predation strategies of leopards and wolves.

Declaration of Competing Interest

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

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