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ORIGINAL PAPER

Does the size of a protected area matter? An assessment of leopard population and habitat usage in a protected area of Shiwalik foothills, Himalaya

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Abstract

Small protected areas, while often considered less important than large protected areas, are also important for the conservation of wide-ranging and low-density large carnivore populations. But these protected areas must have a sufficient prey base, controlled wildlife crime, and interconnectivity with other protected areas in order to be effective. In the foothills of Shiwalik, Himalaya, the 46.8 km^2 Kalesar National Park (KNP) is a dry deciduous forest. We used data collected with camera traps to estimate leopard density using spatial explicit capture-recapture (SECR) model and to model the effects of ecological and anthropogenic variables on habitat use of leopard using generalized linear models. The estimated leopard density was 19.31 ± 5.10 (S.E.) individuals/100 km^2, which is high as compared to many other areas on the Indian subcontinent. Leopard habitat use was positively associated with sambar and wild boar availability, tree number, human disturbance, and distance to road and was negatively associated with chital availability and distance to water. KNP likely has a high density of leopards due to high prey availability and the absence of a dominant competitor (lions or tigers), despite high human disturbance and livestock presence throughout the park. This study will serve as an important baseline for insights into the population dynamics of leopards and creating conservation and management strategies in small protected areas such as KNP. Our results suggest the considerable conservation potential of small protected areas, and we propose that such areas might help to achieve conservation goals.

Keywords Population density · *Panthera pardus* · Camera traps · Space use · Kalesar National Park · Spatial explicit capture-recapture · Generalized linear models

Introduction

Large carnivores often serve as keystone species, but because they are cryptic, wide-ranging, and often occur at low densities, it is often difficult to assess their population dynamics (Rather et al. 2021; Karanth 1995). Ecological (i.e., prey availability and abundance) and anthropogenic (i.e., human footprint and activity) factors play an important role in the distribution and density of large carnivores (Noor et al. 2020; Suraci et al. 2021). Multiple factors can contribute to the low density of large carnivores, including habitat loss, poaching, and prey depletion due to anthropogenic activities (Ripple et al. 2014). The recent advancements in the camera trap and capture-recapture framework have enabled researchers to estimate the population parameters of cryptic carnivores accurately (Rather et al. 2021). Assessing a reliable population estimate of large cryptic carnivores is

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an important aspect for the functioning of an ecosystem and biodiversity conservation for creating effective management goals (Jiménez et al. 2017).

The leopard (*Panthera pardus*) is the most adaptable and widely distributed wild felid across Asia and Africa (Jacobson et al. 2016). There is a huge variation in leopard habitat, and it can be found in the majority of habitats from tropical forests to arid savannah and from alpine mountains to the edges of urban areas (Athreya et al. 2013; Nowell and Jackson 1996; Jacobson et al. 2016). But despite their adaptability, leopard populations are still declining globally due to loss of habitat, reducing prey base, retaliatory killing, and poaching for body parts (Jacobson et al. 2016; Stein et al. 2020). There are lack of detailed population estimates and distribution status available throughout the range of leopards, which prevents accurate estimation of their global-wide population. According to recent assessments, leopards face 61% reduction in global range (Stein et al. 2020), whereas range loss was 48–67% in Africa and 83–87% for Asia. The subspecies *Panthera pardus fusca* had 11% of protected extant range and was estimated a range loss of about 70–72% (Jacobson et al. 2016). Due to reduction in the extant range of leopard, its status was recently changed from “Near Threatened” to “Vulnerable” by the International Union for the Conservation of Nature (IUCN).

Leopards’ ability to live in a diverse range of habitats is partly owing to a high flexibility in their habitat preferences (Hayward et al. 2006). Leopards are energy maximizers and hunt in prey-rich areas with easy catchability of prey (Nowell and Jackson 1996; Balme et al. 2007; Hayward et al. 2006). Anthropogenic disturbance and expansion of human populations lead to habitat reduction and fragmentation for leopards across their range (Jacobson et al. 2016). At a large-scale, leopards’ distribution requires forest cover (Karanth et al. 2009), while at a site-specific level many factors, including vegetation cover, terrain, prey abundance, and human disturbance, influence habitat use of leopards (Prater 2005; Ngoprasert et al. 2007; Kshettry et al. 2017; Allen et al. 2020). The presence of dominant competitors (i.e., tiger and lion) can also affect leopard population density, habitat use (Harihar et al. 2011; Allen et al. 2020), and carcass consumption (Panda et al. 2023). Large carnivore populations are often dependent on having protected areas available, but these areas are also often affected by human disturbance (Chaudhary et al. 2020).

In this study, we used the leopard as a model species to investigate whether the small, protected areas can sustain viable populations of leopards. To our knowledge, there have been few studies conducted in focusing on effect of protected area size on the ecology of leopards. We conducted this study in Kalesar National Park (KNP), which is 46.8 km^2 area in size. To achieve this aim, we firstly (a) estimated the density of leopards and compared the density estimates of leopards in KNP with other study areas conducted in the Indian subcontinent (i.e., India, Nepal, and Sri Lanka) and (b) identified factors influencing habitat use of leopards in KNP, India. The estimation of baseline population density and habitat use of leopard in Shiwalik foothills, Himalaya, is fundamental for understanding and implementing appropriate conservation and management strategies to achieve conservation goals.

Materials and methods

Study area

We performed this study in Kalesar National Park (KNP) Haryana, India (Fig. 1), situated at the foothills of Shiwalik range of the lower Himalayas. The area of KNP is 46.8 km^2 and is situated at the junction of four states: Himachal Pradesh, Uttar Pradesh, Uttarakhand, and Haryana. It is connected with two other protected areas: Col. Sher Jung National Park (27.8 km^2) in Himachal Pradesh and Rajaji Tiger Reserve (820 km^2) in Uttarakhand (Singh et al. 2023a, b; Harihar et al. 2011). The terrain varies from plains to hills, with elevations ranging from 600 to 1100 m, and the temperature varies from 5° C in winter and 46° C in summer (Kalsi 1998). KNP has a subtropical climate, and the park’s habitat is classified as a dry deciduous forest (Champion and Seth 1968). The park has narrow valleys between the hills, where water flows seasonally, but these streams mostly remain dry throughout the year (Kalsi 1998). During the dry season, water is only available in a few water bodies and the KNP faces water scarcity. Sal (*Shorea robusta*) is the dominant tree species present in the forest with a mixture of rohini (*Mallotus philippensis*), sandan (*Desmodium oojeinense*), amaltas (*Cassia fistula*), and khair (*Acacia catechu*). The mammalian species found in KNP are sambar (*Rusa unicolor*), chital (*Axis axis*), barking deer (*Muntiacus muntjak*), nilgai (*Boselaphus tragocamelus*), wild boar (*Sus scrofa*), rhesus monkey (*Macaca mulatta*), common langur (*Semnopithecus entellus*), and the Asian elephant (*Elephas maximus*). Small carnivores like leopard cat (*Prionailurus bengalensis*), Asiatic wildcat (*Felis sylvestris*), rusty-spotted cat (*Prionailurus rubiginosus*), jungle cat (*Felis chaus*), Indian jackal (*Canis aureus indicus*), Asian palm civet (*Paradoxurus hermaphroditus*), and small Indian civet (*Viverricula indica*) are also found here. The reason for absence of tigers in KNP may be due to the small size of protected area and poorly connected wildlife corridors inhabited by humans near Yamuna River (Jhala et al. 2008).

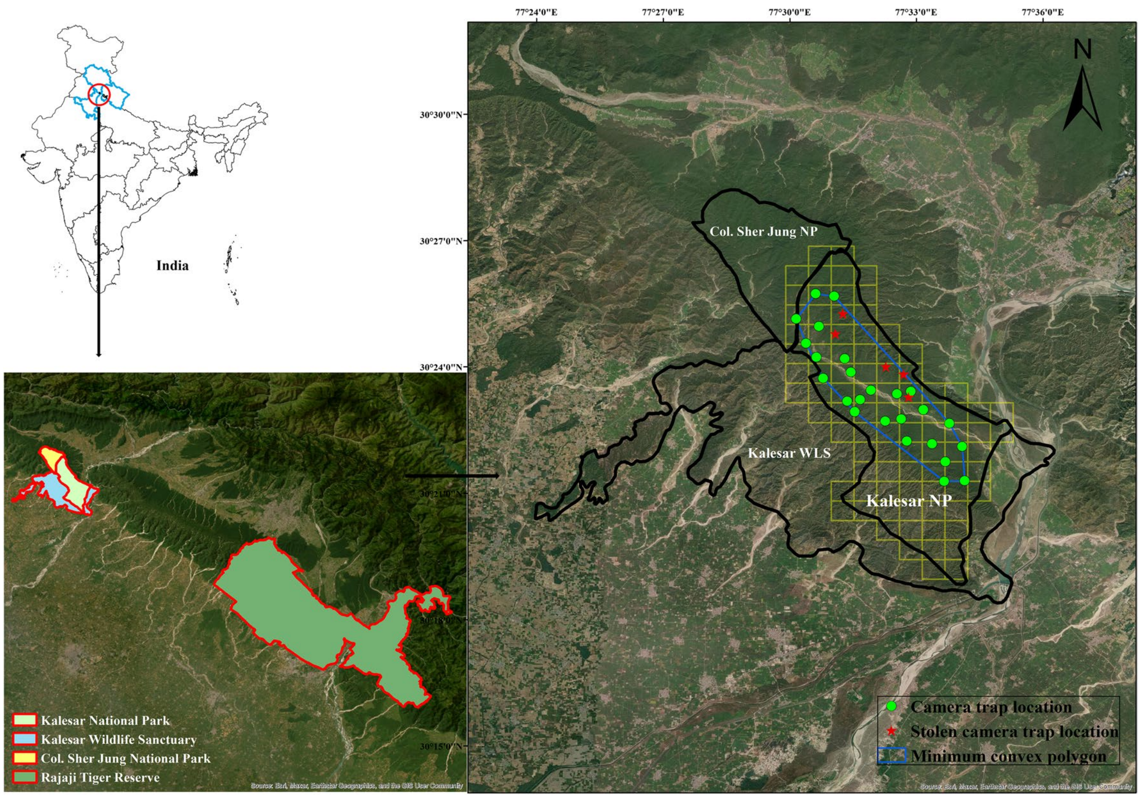


Fig. 1 The minimum convex polygon and specific camera trap locations of our study within Kalesar National Park connected with Kalesar Wildlife Sanctuary, Col. Sher Jung National Park, and Rajaji Tiger Reserve, India

Camera trap sampling

We conducted a reconnaissance survey at KNP in December 2019 to collect indirect signs (tracks, scats, and tree markings) of leopards by walking animal trails, roads, and seasonal water streams. We marked the geo-coordinates of each sign using Global Positioning System (GPS) Garmin etrex-20 (Garmin Corp., Olathe, KS, USA). Then, we overlaid the locations of indirect signs of leopards on a 1×1 km^2 grid map in ArcMap 10.2.2 (ESRI©) to determine the spatial distribution of leopards and select our camera trap sites. Based on this, we decided to use an intertrap distance between the trapping stations of 0.63 km across our 27 km^2 study area. Finally, we deployed camera traps close to the animal trails used most frequently by leopards to ensure that there was a chance of detecting every leopard individual in the study area (Singh et al. 2021).

We used 20 digital camera traps (Cuddeback C1 type; WI, USA) deployed at 30 trapping stations located in two blocks. We placed a single camera trap along the roads and trails at a distance of 5–10 m from the center of roads or trails to capture one flank of leopards. The camera traps were tied to the trees at a height of 30–40 cm above the ground. The camera traps were set at a minimum delay. The camera had white flashes which illuminated up to 30–35 m. We divided the study area into two consecutive non-overlapping blocks and sampled systematically in a phased manner under "survey design 4" (Karanth and Nichols 2002) to cover the minimum convex polygon area of 27 km^2 (Fig. 1). We conducted the sampling from January to April 2020, with 46 days of sampling period in each block. The camera traps were functional throughout the day and night. We checked camera traps twice every week to download images and replace drained batteries. During the sampling period, five camera traps were lost to theft, and therefore, we censored the data from these locations from the analysis and used data from 25 trapping stations.

Data analysis

Density estimation

We identified leopard individuals based on the unique rosette pattern on their coat and examined position and shape of rosettes on the flanks, limbs, forequarters, and tail (Karanth 1995; Henschel and Ray 2003; Sehgal 2020; Singh et al. 2023a, b). Leopards have a different and unique pattern of rosettes on each flank, so we separated photographs of the right and left flanks. We identified the leopards based on their right flanks, had more photo-capture records, and assigned each identified leopard a unique identity number (e.g., L-01, L-02, and L-03). We used Program DENSITY 5.0 to estimate the density of leopards (Efford et al. 2009) using the maximum likelihood (ML)-based spatially explicit capture-recapture (SECR) model. SECR models has two parameters: ($g0$) estimation detection probability at the center of an individual's home range and (σ) scale of animal movements from the center of the home range (Efford 2018). We used the Poisson distribution model and modeled the capture probability of an individual in a particular trap without knowing the center of its home range. We created a buffer of 10 km around the trapping grids to ensure that no individual leopard outside of the buffer region had any reasonable probability of being photographed by the camera trap during the survey (Singh et al. 2014). We used half-normal spatial capture probability function to model the assumption of equal probability of capture of all individuals.

We compared the leopard densities from our study to various protected areas across the Indian subcontinent. We searched Google Scholar for keywords "leopard", "density", "Panthera pardus", and "population" and set the custom time range between 2007 and 2022. We then read each entry and eliminated duplicate reports and mismatched publications, as well as those not from peer-reviewed journals. We reviewed the remaining 14 SECR and conventional MMDM methods studies performed on density of leopards between 2007 and 2022 to compare with our results.

Habitat use

We characterized each camera trap site by recording the predictive ecological and anthropogenic variables. The species we considered as prey were sambar (*Rusa unicolor*), chital (*Axis axis*), wild boar (*Sus scrofa*), barking deer (*Muntiacus muntjac*), rhesus macaque (*Macaca mulatta*), peafowl (*Pavo cristatus*) and livestock, because all of these species are preyed on by leopards (Hayward et al. 2006; Mondal et al. 2012a; Kshettry et al. 2018). We assessed the prey availability by estimating the relative abundance of each prey species using camera traps. To calculate the relative abundance indices (RAI) of each prey species, the number of independent (camera trap capture > 30 min apart from each other) was divided by trap nights at each site and then multiplied by 100. We considered a 10 m radius circular plot at each site to record canopy cover (%), shrub cover (%), and tree number (Sehgal 2020). Distance to water and road (km) was estimated using Euclidean distance from the camera trap location to the nearest water and road present, and elevation (m) data was extracted using ArcMap (version 10.2.2).

We tested all covariates for multicollinearity by standardizing the variables and performing the Pearson correlation analysis and dropped highly correlated predictor variables (> 0.70) from further analysis (Minitab version 19.1). We used generalized linear models (GLMs) to assess the effect of predictor variables (ecological and anthropogenic) on habitat use of leopard (leopard RAI). We fit GLMs with the Poisson distribution with a log link. We created a list of all possible models to examine the relationship between the response and predictor variables (Guerisoli et al. 2019) using function "dredge" in the "MuMIn" package (Bartoń 2020) in R-studio (version 3.1.2; R Development Core Team 2011). Models were constructed using all combinations of predictors and were ranked using the Akaike information criterion corrected for small samples (AICc). We used ΔAIC and AIC weight (w) to select the best fit models (ΔAIC < 2; Burnham and Anderson 2002). We used model averaging for models with ΔAIC < 2 to understand the most important predictor variables following Burnham and Anderson (2002).

Results

Sampling effort

From January to April 2020, we obtained 199 photo captures (90 left and 109 right flanks) of leopards over 1150 camera trap nights. We detected leopards at 21 out of the 25 trapping stations. Out of these photographs, 83.5% were suitable for identifying individual leopards, and we discarded the remaining 14.6% of photographs from the analysis. We used right flank data because the number of photo captures and identified individuals was more than the left flank data, and we were able to identify 22 individual leopards from the right flank data. The closure test suggested that leopard population was closed during the sampling period ($z = -0.42$, $p = 0.33$). The 22 unique leopard individuals were stabilized on the 30th day of sampling with 93 photo captures (Fig. 2).

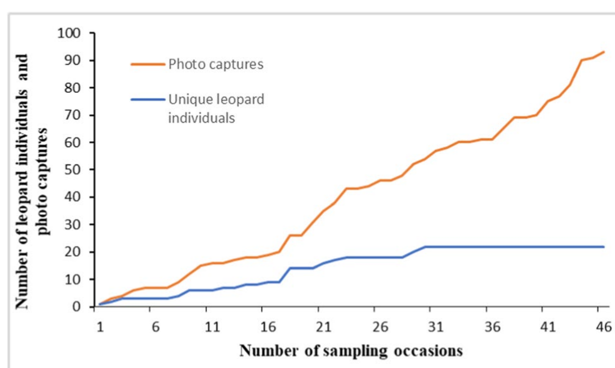


Fig. 2 Cumulative number of unique leopard individuals and photo captures in Kalesar National Park, India

Table 1 Literature review of leopard studies (including study reference, location, and forest types) conducted in protected areas of the Indian subcontinent. We provide the population model (abbreviation from Efford et al. 2009, abbreviation from Royle et al. 2009a, b, and so on) the effective trapping area, population size, and density estimate (as leopards per 100 km^2)

Author	Location	Forest type	Model used to estimate density	Effective trapping area (km^2)	Density estimate (leopards/100 km^2) ± SE
Surve et al. (2015)	Sanjay Gandhi National Park, India	Moist deciduous forest	Efford (2015)	140	21.55 ± 4.6
Chaudhary et al. (2022)	Gir Protected Area, India	Dry teak deciduous forest	Efford (2018)	177	19.9 ± 3.8
Present study	Kalesar National Park, India	Dry deciduous forest	Efford et al. (2009)	27	19.31 ± 5.10
Kittle and Watson (2017)	Horton Plains National Park, Sri Lanka	Montane Forest	Efford et al. (2016)	172	13.40 ± 6.3
Kalle et al. (2011)	Mudumalai Tiger Reserve, India	Moist and dry deciduous forest	Efford (2009)	184.53	13.17 ± 3.15
Majumder (2011)	Pench Tiger Reserve, India	Moist and dry deciduous forest	Efford (2004)	607	9 ± 4
Singh et al. (2023ab)	Ranthambhore Tiger Reserve	Tropical thorny forest	Efford (2009; 2010)	233 (MCP)	8.8 ± 2.8
Edgaonkar et al. (2007)	Satpura National Park, India	Moist and dry deciduous forest	Efford (2007)	110.34–151.47	7 ± 2.1–10 ± 5.1
Thapa et al. (2014)	Parsa Wildlife Reserve, Nepal	Dry deciduous forest	Borchers and Efford (2008)	736.3	3.78 ± 0.85
Borah et al. (2013)	Manas National Park, India	Alluvial floodplain and subtropical forest	Borchers and Efford (2008)	414.2	3.40 ± 0.82
Mondal et al. (2012b)	Sariska Tiger Reserve, India	Dry deciduous and thorn forest	Efford et al. (2004)	250.3	3.3 ± 1.2
Selvan et al. (2014)	Pakke Tiger Reserve, India	Evergreen forest	Borchers and Efford (2008)	257.2	2.99 ± 1.13
Ramesh et al. (2012)	Kalakad-Mundanthurai Tiger Reserve, India	Wet evergreen forest	Efford (2009)	320	2.8 ± 2.0
Noor et al. (2020)	Dachigam National Park, India	Moist temperate forest	Royle et al. (2009ab)	140	2.8 ± 1.18
Harihar et al. (2011)	Chilla, Rajaji National Park, India	Moist and dry deciduous forest	Royle et al. (2009a)	NA	2.07 ± 1.63
Wang and Macdonald (2009)	Jigme Singye Wangchuck National Park, Bhutan	Broadleaf to coniferous forest	Wilson and Anderson (1985)	1542	1.04 ± 0.01

NA not available

Density estimation

The estimated detection probability ($g0$) at the center of an individual's home range for leopard was 0.021 ± 0.004 (S.E.). However, the scale of animal movements from the center of the home range (σ) was 1.51 ± 0.17 (S.E.) km. The leopard density in KNP was 19.31 ± 5.10 (S.E.) (leopards/100 km^2) (Table 1). From the compared 14 studies, our study reported the third highest leopard density in the Indian subcontinent (Table 1).

Table 2 Results of generalized linear model (GLM) used to assess the habitat use of leopards in Kalesar National Park, India. Only parameters for the best set of models with ΔAIC < 2 are reported. *df* degrees of freedom, *log lik* log likelihood function, *AICc* Akaike's information criterion for small sample size, *ΔAIC* difference in value of Akaike's information criterion between the focal model and the top-ranked model, *w* weight. Variables are described in "Materials and methods"

Covariates	df	Log lik	AICc	ΔAIC	*w*
Barking + chital + human + road + sambar + tree + water + wild	9	− 85.67	201.34	0.00	0.25
Chital + human + road + sambar + tree + water + wild	8	− 88.30	201.61	0.27	0.22
Chital + human + peafowl + road + sambar + tree + water + wild	9	− 86.90	203.80	2.46	0.07

Habitat use

We performed Pearson correlation analysis and did not find any strong correlations among our predictor variables, so we included all of them in our analysis. We had three top models, with the habitat use of leopards best predicted by the model of availability of chital, sambar, wild boar, tree number, human disturbance, and distance to water and road ($w = 0.25$; Table 2).

We estimated the coefficients of predictor variables using model-averaged equations following the criteria $\Delta AIC < 2$ (Table 2). Based on the model averaging, the availability of sambar ($\beta = 0.0098$, $p < 0.05$), wild boar ($\beta = 0.0174$, $p < 0.05$), tree number ($\beta = 0.0716$, $p < 0.05$), human disturbance ($\beta = 0.0020$, $p < 0.05$), and distance to road ($\beta = 0.2431$, $p < 0.05$) were positively associated with habitat use of leopards (Table 3; Fig. 3a, b, d, f) while the availability of chital ($\beta = -0.0086$, $p < 0.05$) and distance to water ($\beta = -0.7356$, $p < 0.05$) were negatively associated (Table 3; Fig. 3c, g). However, availability of barking deer ($\beta = -0.0273$, $p = > 0.05$), peafowl ($\beta = -0.0014$, $p = > 0.05$), rhesus macaque ($\beta = -0.0002$, $p = > 0.05$), livestock ($\beta = -0.0008$, $p = > 0.05$), shrub cover ($\beta = -0.0001$, $p = > 0.05$), elevation ($\beta = -0.0002$, $p = > 0.05$), and canopy cover ($\beta = -0.001$, $p = > 0.05$) had no significant effect on leopard habitat use (Table 3).

Discussion

Leopard density

The estimated density of leopards that we found in KNP (19.31 ± 5.10 leopards/100 km^2) is one of the highest leopard population densities recorded in the Indian subcontinent (Table 1). The high availability of prey may be one of the main reasons for the high density of leopards in KNP (Karanth et al. 2004; Sehgal 2020). A study published by Sehgal et al. (2022) from the same study area estimated high relative abundances of leopard's preferred prey species: wild boar (18.43), sambar (38.34), peafowl (10.78), and chital (24.47), as well as rhesus macaque (16.26) and barking deer (2.17). Similar high-density estimates of leopards have also been reported from other protected areas like Gir Protected Area (19.9 ± 3.38; Chaudhary et al. 2022), Ranthambhore Tiger Reserve (8.8 ± 2.8; Singh et al. 2023a, b), Mudumalai Tiger Reserve (13.17 ± 3.15; Kalle et al. 2011), and Horton Plains National Park, Sri Lanka (13.40 ± 6.3; Kittle and Watson 2017), due to available high prey biomass (Table 1).

Table 3 Generalized linear model (GLM) average coefficient (β) with standard error (SE) of the variables to explain the habitat use of leopards in Kalesar National Park, India

Covariates	Coefficient (β)	Standard error	p value
Intercept	0.6115	0.6084	0.3372
Distance to road	0.2431	0.0826	0.0051**
Tree number	0.0716	0.0170	< 0.0001***
Wild boar	0.0174	0.0037	< 0.0001***
Human disturbance	0.0020	0.0005	0.0001***
Sambar	0.0098	0.0026	0.0002***
Shrub cover	0.0001	0.0009	0.9035
Rhesus macaque	−0.0002	0.0013	0.8796
Elevation	−0.0002	0.0009	0.8177
Livestock	−0.0008	0.0028	0.7864
Canopy cover	−0.0011	0.0040	0.7779
Peafowl	−0.0014	0.0037	0.6978
Chital	−0.0086	0.0024	0.0007***
Barking deer	−0.0273	0.0368	0.4688
Distance to water	−0.7356	0.2781	0.0116*

Statistically significant at $p = 0$ '***', 0.001 '**', 0.01 '*'

Interspecific competition from a dominant member of the guild can also affect the abundance of subordinate predators (Chaudhary et al. 2022). After 18 years, a tiger was recently photographed after the sampling duration (Feb 2023) in the study region, possibly dispersed from Rajaji National Park, which is 132 km away (Haryana Forest Department personal communication), so it may affect leopard population in the future. A study in a similar and connected protected area (Rajaji National Park) by Harihar et al. (2011) showed that an increase in tiger abundance over the years results in a decreased abundance of leopards. In the absence of tigers, leopards expand their habitat and prey niche to occupy the entire area (Mondal et al. 2012b; Sehgal et al. 2022). But some protected areas favored high leopard density in coexistence with dominant competitors (tiger or lion) (Singh et al. 2023a, b). Study carried out in Gir Protected Area and Ranthambhore and Mudumalai Tiger Reserve by Chaudhary et al. (2022), Singh et al. (2023ab), and Kalle et al. (2011) found that leopard exists at high density despite the high abundance of lions and tigers. This indicates a successful avoidance of dominant competitors by leopards, differential habitat selection, and high prey base availability.

In this study, we used a maximum likelihood-based SECR model to estimate leopard density. MMDM models were found to be unreliable and inconsistent in estimating density as compared to spatial models (Kalle et al. 2011). The maximum likelihood model is appropriate to use and did not show any significant dissimilarity to the Bayesian model (Kalle et al. 2011), and due to this reason, we used the maximum likelihood model in this study. One of the main drawbacks of the Bayesian models is that they are extremely sensitive to the buffer width in comparison with the likelihood method (Jhala et al. 2008; Kalle et al. 2011). The spatial explicit methods are non-biased by an informal estimation of an effective survey area and thus recommended to use (Borchers and Efford 2008; Noss et al. 2012). But there may be certain factors in sampling design and data analysis that could cause biases in density estimates, including a smaller trapping area. As such, the main drawback of this study was the small trapping area (27 km^2). The survey area should preferably be at least the size of the largest home range of a male leopard, as suggested by other studies on large felids (Karanth and Nichols 1998; Jhala et al. 2008); however, our SECR models have been shown to produce unbiased density estimates despite small trapping area (Tobler and Powell 2013); therefore, our density estimates are likely accurate.

Habitat use

Our results revealed that habitat use of leopards in KNP had positive relationships with distance to road, tree number, human disturbance, wild boar abundance, and sambar abundance (Chaudhary et al. 2020; Mondal et al. 2013). In contrast, distance to water and chital abundance had a negative relationship with leopard's habitat use.

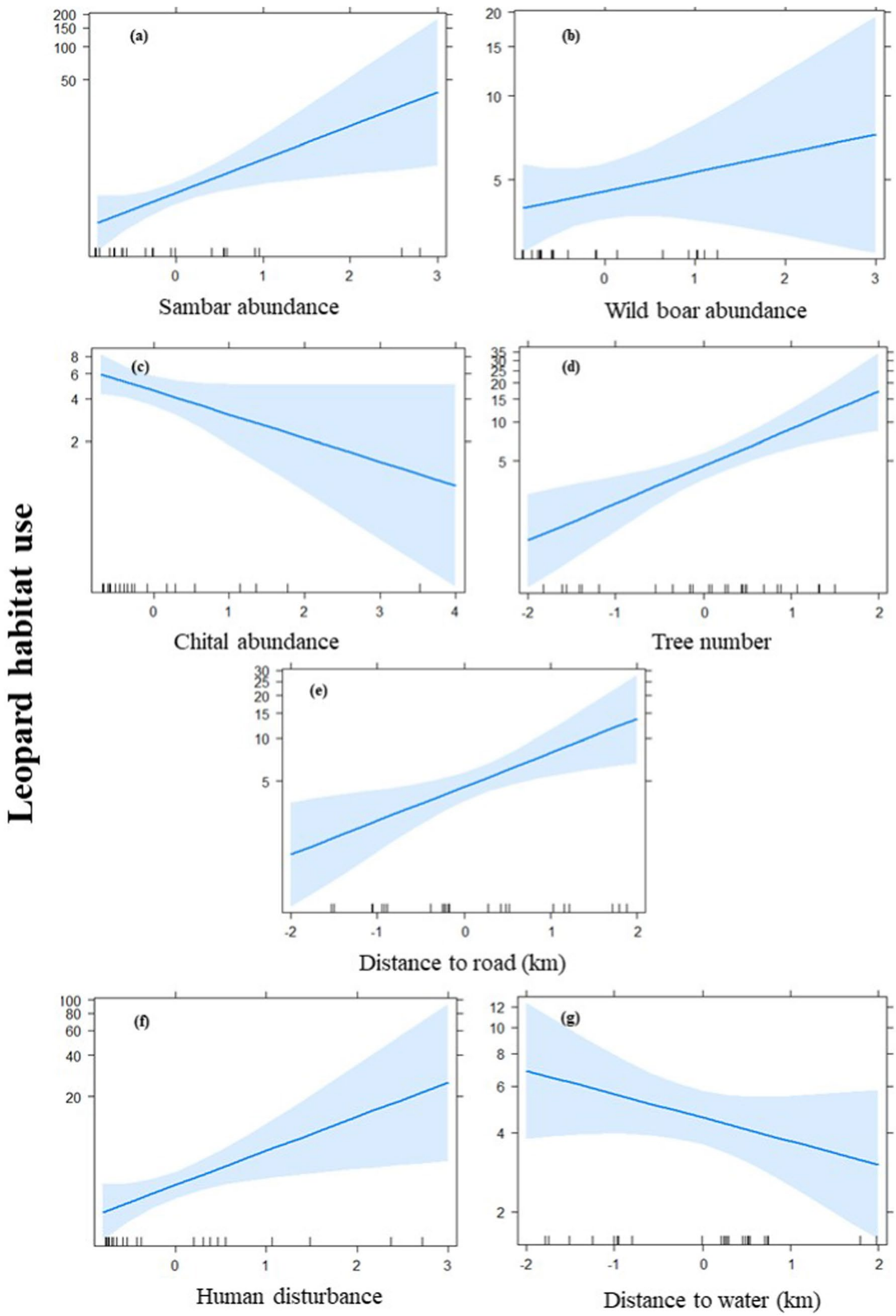
Prey base depletion is a crucial factor in the global reduction of large predator populations since abundant prey is essential for the survival of large carnivores (Taghdisi et al. 2013; Wolf and Ripple 2016). Previous studies in Africa (Burton et al. 2012; Kane 2014; Balme et al. 2019; Searle et al. 2020) and India (Chaudhary et al. 2020) suggested that leopard habitat use was positively influenced by prey availability. Sambar and wild boar constitute 21.42% and 0.85% of biomass consumption of leopards in Gir National Park, India (Zehra et al. 2017), which has similar prey species composition and habitat type to our study area, and sambar and wild boar were predicted as the most preferred prey species for leopards in our study area (Sehgal et al. 2022). The positive association of leopard habitat use with wild boar abundance may be the result of similar habitat preferences and high spatial and temporal overlap (Chaudhary et al. 2019; Sehgal et al. 2022). The studies on food habits of leopard suggested chital being the most preferred prey and constituted the highest (38.57%) in leopards' biomass consumption (Zehra et al. 2017; Hayward et al. 2006) and showed negative habitat use association with leopard in our study which might be due to its confined distribution to specific habitats and differences in terrain use (Sehgal et al. 2022). Our findings imply that leopard habitat use is driven by the availability of prey of their preferred body size rather than by the presence of a particular species. This is consistent with the species' ability to adjust its diet to a variety of prey based on the resources available and its generalist feeding behavior (Hayward et al. 2006).

In regard to anthropogenic disturbance, leopard habitat use had positive relationships with human disturbance and distance to road, indicating that leopards were more abundant further from anthropogenic disturbance. Very high and widespread human presence was found in the park (87% camera stations) due to tourist traffic, fuel wood and non-timber forest product (NTFP) collectors, poachers, and forest staff patrolling. Logging activities reduce the canopy cover and density of large trees resulting in the opening of forest habitats and changes in forest structure (Ngoprasert et al. 2007). The habitat use of leopard increases with increasing distance to roads, suggesting a possible edge effect. Vehicular traffic is likely the reason for reduced habitat use of leopards near roads.

Large carnivores often select areas with high canopy cover and tree density, which influence their hunting strategies (Abade et al. 2014; Chaudhary et al. 2022). The tree number is positively associated with leopard habitat use. This is likely because leopards are ambush predators, who avoid open forests and prefer areas with an intermediate cover and thick vegetation helping to hunt the prey (Hayward et al. 2006; Balme et al. 2007; Kittle et al. 2014). Grasslands were avoided by leopards, likely because of less cover as compared to other hunting areas (Balme et al. 2007). Water is an important limiting factor for species distribution in dry deciduous forests (Mondal et al. 2013; Chaudhary et al. 2020), and we found that leopards preferred to use the habitat nearby water holes. KNP has natural as well as artificial water bodies which are regularly monitored by park staff due to the scarcity of water during the summers.

Conservation implications and recommendations

This study will serve as an important baseline for the long-term monitoring of leopards in Shiwalik foothills. Due to a lack of proper baseline data, local extinction of large carnivores has occurred from various habitats around the world (Weber and Rabinowitz 1996). KNP harbors a high density of leopards despite high human disturbance and livestock presence throughout the park, which should be the subject of concern for the park managers. Protected area management should focus on regulating human access across their boundaries (Rowcliffe et al. 2004) by (i) patrolling park boundaries parallel to roads and (ii) imposing penalties on illegal incursions (Ngoprasert et al. 2007). The survival of large carnivores depends on an abundant prey base (chital, sambar, and wild boar) which should be a focus of park management (Sehgal et al. 2022). During summers, water scarcity is the major cause of concern in the park; regular monitoring and supply of water to water bodies is recommended. KNP has forest contiguity from Rajaji Tiger Reserve to Corbett Tiger Reserve, Uttarakhand, and Col. Sher Jung National Park, Himachal Pradesh (Jhala et al. 2008). This makes it an important corridor for elephants, leopards,


Leopard habitat use
(a)
200
150
100
50
0
1
2
3
Sambar abundance
(b)
20
15
10
5
0
1
2
3
Wild boar abundance
(c)
8
6
4
2
0
1
2
3
4
Chital abundance
(d)
35
30
25
20
15
10
5
-2
-1
0
1
2
Tree number
(e)
30
25
20
15
10
5
-2
-1
0
1
2
Distance to road (km)
(f)
100
80
60
40
20
0
1
2
3
Human disturbance
(g)
12
10
8
6
4
2
-2
-1
0
1
2
Distance to water (km)

◂**Fig. 3** The relationship between leopard abundance and predictor variables (ecological and anthropogenic): **a** leopard habitat use and sambar abundance, **b** leopard habitat use and wild boar abundance, **c** leopard habitat use and chital abundance, **d** leopard habitat use and tree number, **e** leopard habitat use and distance to road, **f** leopard habitat use and human disturbance, and **g** leopard habitat use and distance to water, in Kalesar National Park, India

and tigers. This study can contribute to the assessment of conservation status and implement mitigation measures using the information on population density and habitat use of leopards. Long-term monitoring of leopards is required to get better insights into population dynamics, and further studies are needed to inform conservation planning for wildlife corridors.

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Data Availability The data that support the conclusions of this study are accessible upon request from the corresponding author.

Declarations

Ethics approval This study was conducted with the approval from Haryana Forest Department (letter no. 2062, effective from 04–09-2017). We followed all guidelines for animal care and scientific research ethics.

Competing interests The authors declare no competing interests.

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