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continued on the back inside cover

Cover: Oil painting of Humpback Whale *Megaptera novaeangliae*. © R. Mahesh.



Small Wild Cats Special Series

Distribution, habitat use, and abundance of the Caracal *Caracal caracal* (Schreber, 1776) (Mammalia: Carnivora: Felidae) in a semi-arid Indian landscape

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Abstract: We collected Caracal *Caracal caracal* presence locations using camera traps in the human-dominated Kailadevi landscape in southeastern Rajasthan, India. Our survey effort of 5,258 camera trap days at 177 camera trap locations in a sampling area of about 600 km² yielded 92 independent photocaptures at 54 locations between January 2020 and March 2022. Relative abundance index values indicate that the Caracal has been consistently photocaptured over the three sampling sessions. We used these data to model potential Caracal habitats at the landscape level using MaxEnt, and we used generalized linear models to identify the factors influencing Caracal detection site at the camera trap level. The habitat suitability results indicate that, out of the entire extent of 109,663 km² spanning the Greater Ranthambhore Ecosystem from eastern Rajasthan to western Madhya Pradesh, an area of 14,284 km² constitutes suitable habitat for the Caracal, of which about 26% occurs within the protected area network. Of all the suitable habitats, about 1,230 km² was classified as highly suitable, with 41% distributed across the protected area network. The Ranthambhore–Kailadevi–Dholpur cluster harbours the largest contiguous patches. Suitable Caracal habitats showed positive association with open natural ecosystems, rugged terrain, and proximity to water, but negative association with human disturbance. At camera trap level, site use intensity of the Caracal was positively influenced by rugged terrain, open natural ecosystems, proximity to water, and distance from human settlements. Based on published estimates for home range size and the extent of suitable habitat predicted by the MaxEnt model, Kailadevi can potentially support 8 (4–24) male and 23 (14–55) female Caracal home ranges, followed by Ranthambhore with 4 (2–11) male and 10 (6–24) female home ranges, and Dholpur with 3 (2–8) male and 7 (5–17) female home ranges. In total, the Ranthambhore–Kailadevi–Dholpur landscape can potentially harbour 55 (33–139) Caracal home ranges, providing a preliminary indication of the potential population supported by the currently available suitable habitat. Our findings highlight the importance of conserving the open natural ecosystems, especially ravines, which provide refuge for the Caracal in this human-dominated landscape. Conservation strategies should prioritise to safeguard the potential Caracal habitats and maintain connectivity between these habitats to secure its long-term persistence.

Keywords: Camera traps, generalised linear model, home ranges, MaxEnt, open forests, population, Rajasthan, Greater Ranthambhore Ecosystem, ravines, small wild cat.

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Author details: Mohammad Mairaj (MM) and Ramanand Bhakar (RB) are affiliated with the Rajasthan Forest Department, Jaipur. Dhruv Jain (DJ) and Ayan Sadhu (AS) are affiliated with the Tiger Cell at the Wildlife Institute of India, Dehradun.

Author contribution: MM and AS conceptualised the study. MM and RB carried out the fieldwork and arranged the logistics. AS and DJ conducted the analyses. AS led the manuscript writing and interpretation of results. All authors reviewed the final draft, provided critical comments, and approved the final version of the manuscript.

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INTRODUCTION

The global decline in carnivore populations is largely attributed to habitat loss, fragmentation, and direct persecution by humans (Ripple et al. 2014). The ecology and distribution of many carnivore species remain poorly understood, posing a major challenge to formulating effective conservation strategies (Glen et al. 2014). The Caracal *Caracal caracal* is widely distributed in Africa, western and central Asia, and western parts of the Indian subcontinent (Avgan et al. 2016). Populations in northern Africa and parts of Asia are thought to have declined, mainly due to habitat conversion for human use (Avgan et al. 2016). The Caracal lives in diverse habitats, including savannas, arid regions, scrublands, and dry forests (Veals et al. 2020). In the Mediterranean region of southern Türkiye, it prefers heterogeneous pine forests with canopy closure below 70% (Ünal et al. 2020; İlemin et al. 2023). In Iran, it has been recorded in forest steppes, semi-arid montane woodlands, arid hilly terrain, well-vegetated foothills, dry riverbeds, and along the semi-desert coast of the Persian Gulf (Farhadinia et al. 2007; Ghoddousi et al. 2009; Moqanaki et al. 2016; Jamali et al. 2024).

Across much of its African range, the Caracal is more frequently associated with wooded grasslands and riparian zones within savannas than with contiguous forests, reflecting a preference for ecotonal and open habitats with sufficient cover and prey availability (Hanekom & Randall 2015; Ramesh et al. 2017; Mwampeta et al. 2020). These habitat associations highlight its reliance on structural complexity in vegetation and terrain to facilitate ambush predation and refuge from larger carnivores (Davis et al. 2023). Its low density makes it challenging to monitor, and the paucity of dedicated studies results in a lack of comprehensive data on its distribution and ecological requirements (Avgan et al. 2016).

Globally, the Caracal is classified as Least Concern on the IUCN Red List of Threatened Species (Avgan et al. 2016). In India, it is legally protected under Schedule I of the Wild Life (Protection) Amendment Act, 2022 (Ministry of Law and Justice 2022). Photographic records are limited to protected areas in southeastern Rajasthan (Singh et al. 2014; Khandal et al. 2020; Jhala et al. 2021; Thakar et al. 2025), desert landscapes of western Rajasthan (TNN 2026), and outside protected areas in northwestern Gujarat (Khandal et al. 2020; Jhala et al. 2021; Ganguly 2022; Mukherjee & Nandini 2024). Previous studies in India indicate that the Caracal prefers open forests with abundant rodent and ground-

dwelling birds (Mukherjee et al. 2004; Jhala et al. 2021).

Understanding the habitat use of the Caracal is crucial for developing effective conservation strategies. Therefore, we aimed to identify key environmental factors influencing Caracal distribution in the Kailadevi landscape by addressing the following research questions:

1. Which ecological and anthropogenic factors influence the distribution of the Caracal?
2. How do anthropogenic pressures affect Caracal occurrence in the region?

Study Area

The study was conducted in Kailadevi Wildlife Sanctuary and its adjoining areas, which form the northern extension of the Ranthambhore Tiger Reserve (Figure 1). This protected area is situated in a semi-arid transition zone between the Thar Desert and peninsular India (Rodgers & Panwar 1988). It is bounded by the Banas River to the southwest and the Chambal River to the east (Yadav 2022). Its rugged terrain features rocky slopes, ravines, cave-like depressions and scrub forests, with scattered water sources and villages (Yadav 2022). The vegetation of this landscape is dominated by northern tropical dry deciduous forests and scrubland, with *Anogeissus pendula* covering 80% of the area, followed by *Acacia catechu*, *Butea monosperma*, and *Ziziphus* species (Yadav 2022). Moist valleys support species like *Ficus glomerata*, *Syzygium cumini*, and *Mitragyna parviflora*, while the undergrowth includes *Flacourtia indica*, *Grewia*, and *Barleria* species. Grass diversity varies with terrain and grazing pressure from *Apluda mutica* on slopes to *Aristida* in heavily grazed areas, and *Vetiveria* species along the streams (Ayan Sadhu, pers. obs.).

Pastoral communities living in villages graze their livestock in forest areas inside the sanctuary; this, coupled with the extraction of timber, fuelwood, and fodder leads to considerable degradation of wildlife habitat (Yadav 2022). However, the traditional lifestyle of the people allows space for wildlife that can tolerate low to medium human disturbances (Jhala 2013). Despite the anthropogenic pressure, Kailadevi Wildlife Sanctuary supports a low-density population of the Tiger *Panthera tigris* (Sadhu et al. 2017). It also harbours the Leopard *P. pardus*, Indian Wolf *Canis lupus*, Golden Jackal *C. aureus*, Striped Hyena *Hyaena hyaena*, Sloth Bear *Melursus ursinus*, Jungle Cat *Felis chaus*, Afro-Asiatic Wildcat *F. lybica*, and Honey Badger *Mellivora capensis* (Jhala et al. 2020). Ungulates like Nilgai *Boselaphus tragocamelus*, Chital *Axis axis*, and

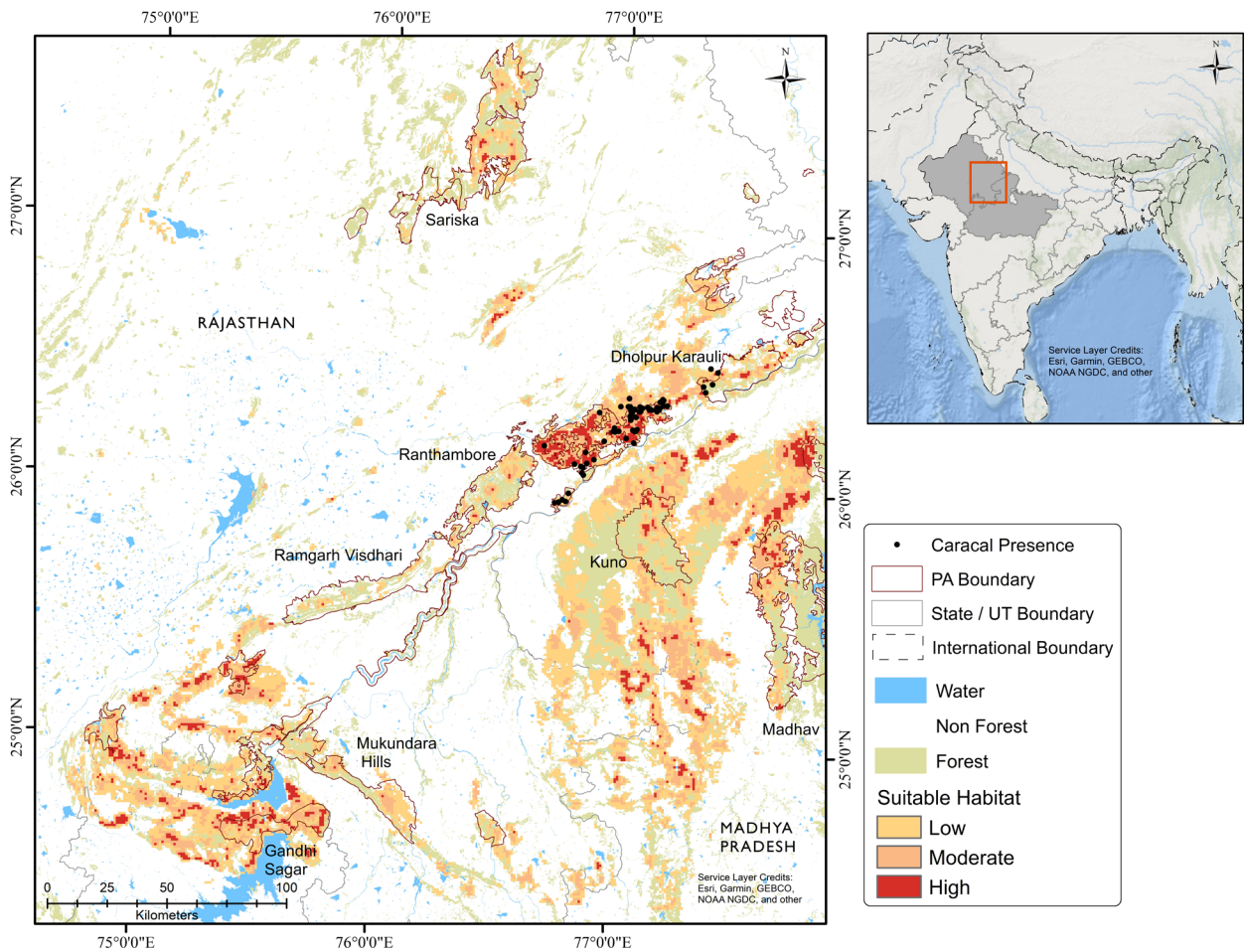


Figure 1. Map showing potentially suitable habitat of the *Caracal* predicted using species distribution modelling (MaxEnt) in the semi-arid western Indian landscape. The class 'Forest' includes scrublands, grasslands, open forests, moderately dense and dense forests.

Chinkara *Gazella bennettii* occur at low densities (Jhala et al. 2020), making Kailadevi Wildlife Sanctuary crucial for wildlife conservation.

While camera trapping was conducted in Kailadevi Wildlife Sanctuary, the potential distribution of the *Caracal* was predicted across the Greater Ranthambhore ecosystem comprising Ranthambhore National Park, Kailadevi Wildlife Sanctuary, Kuno National Park, Ramgarh Vishdhari Tiger Reserve, Mukundara Hills Tiger Reserve, Dholpur Karauli Tiger Reserve and adjoining areas (Qureshi et al. 2023), and Sariska Tiger Reserve (Figure 1).

MATERIAL AND METHODS

We used camera traps to record *Caracal* presence in the Kailadevi landscape and modelled potential *Caracal* habitats in the larger landscape to direct future conservation investments. Furthermore, we sought to

identify the most impactful factors influencing *Caracal* distribution in this landscape.

Camera Trapping

As a part of the routine Tiger and co-predators monitoring surveys in the Kailadevi landscape, we conducted surveys between 2020 and 2022 using Cuddeback X-Change™ camera trap models. We programmed the camera traps to take one photograph per trigger with a time and date stamp on every photograph. We set the delay between two consecutive photographs to 'Fast As Possible' mode and turned off video mode. Each camera trap was assigned a unique ID.

We surveyed the entire area by foot to record the presence of carnivores from direct and indirect evidence like pugmarks and scat, and placed camera traps on the basis of the intensity of carnivore sign encounters. We also considered the knowledge of forest guards and local people acquainted with the area to find suitable areas

for camera trap deployment. No bait was used. The coordinates of camera trap locations were determined using handheld Garmin 72™ and Garmin Etrex® 10 GPS devices set to WGS 84 geodetic datum.

The camera traps were deployed singly and active for 24 hours per day, henceforth called camera trap day. At 3–5 locations close to human settlements, we removed camera traps during the daytime to avoid theft or damage. People and livestock frequently visited these locations in the daytime, whereas wildlife was mostly active during the twilight and night hours. The camera traps were operational for about 30 days with a range of 8–44 days and were inspected every 2–3 days to ensure proper functionality and data retrieval. The photographs obtained were archived camera trap ID-wise and segregated to the species level.

When the interval between two or more consecutive photographs of the Caracal at the same camera trap location was more than 30 minutes, we considered them as independent photocaptures (O'Brien et al. 2003).

Relative Abundance Index

Relative abundance index (RAI) is widely used to monitor the trend of wildlife abundance, especially when individual identification is not possible (O'Brien et al. 2003). We defined the RAI of the Caracal as the number of independent photocaptures at each location per 100 camera trap days at this location (O'Brien et al. 2003). We averaged the RAI values obtained for all the locations with and without independent photocaptures in each sampling year to estimate the trend in Caracal abundance over three years of sampling.

$$RAI_{\text{Caracal}} = \text{Average} \left(\frac{\text{Independent photocapture of } \text{€ camera trap } i}{\text{Survey effort of camera trap } i} \times 100 \right)$$

Preparation of Variables

Ecologically meaningful variables like distance from waterbodies, distance from grasslands-scrubland ecosystems, human footprint index, terrain ruggedness were selected (Appendix 1). All covariates were extracted at a 1 km² spatial resolution and projected using the WGS 1984 Lambert Conformal Conic (LCC) projection system. Variables were tested for collinearity, and only non-correlated variables ($r \leq |0.7|$) (Appendix 2) were used in the same model.

Habitat Suitability Modelling

We used Maximum Entropy Species Distribution Modelling (MaxEnt; Phillips & Dudík 2008) to predict

suitable Caracal habitat within the study area. MaxEnt uses known presence locations and environmental variables to estimate species distribution ranging from '0' for unsuitable to '1' for highly suitable (Phillips et al. 2017). We used 80% of the presence points for model training and reserved 20% for testing. We performed 100 bootstrap runs to assess model uncertainty and kept 10,000 background points. The model was configured using linear and quadratic functions to analyse relationships between species presence and environmental factors. The output format was set to 'logistic', which provides a theoretically stronger interpretation than the logistic transform, particularly in modelling moderately high suitability areas (Phillips et al. 2017). The regularisation multiplier was optimised at 1.0 through incremental testing with a range of 0.7–1.5 in 0.1 intervals, and the highest area under the curve (AUC) value determines the best combination. Habitat suitability was categorised based on the average 'maximum test sensitivity plus specificity logistic threshold'. Model selection was guided by the AUC of the receiver operating characteristic (ROC) plot, comparing five ecologically relevant models. The final model with the highest AUC value was considered the best representation of Caracal habitat suitability. Variable selection and model evaluation were based on mean AUC values and the contribution of individual and combined variables (Appendix 3).

Generalised Linear Modelling

To assess the factors influencing Caracal habitat use, we employed generalized linear models (GLMs), a flexible statistical framework that extends linear regression to accommodate non-normal response variables by specifying an appropriate error distribution and link function (Guisan et al. 2002; Fox 2003). Given our binary response data (presence = 1, absence = 0), we used logistic regression, a GLM with a binomial error distribution and a logit link function (Agresti 2013). This approach allowed us to model the probability of Caracal presence as a function of key habitat variables, while addressing the bounded nature (0, 1) of binary outcomes (Zuur et al. 2009).

We extracted covariates at each camera trap presence point within a 500-m radius to discern the factors governing the habitat use of the Caracal in our study area. Model selection was conducted using a backward elimination process where the model with lowest Akaike's information criterion (AIC) value indicated the best fit model (Burnham et al. 2011, Appendix 4). We initially included all ecologically plausible predictor

variables and iteratively removed non-significant terms ($p > 0.05$). Predictor significance was evaluated at a 95% confidence level of its coefficient.

Potential Population Size

We used the extent of suitable habitat predicted by the MaxEnt model above the cumulative threshold to approximate the potential Caracal population. We recognise that habitat suitability does not equate to species occupancy. Therefore, we restricted the extrapolation of home range based estimates exclusively to areas with consistent evidence of Caracal presence, i.e., Kailadevi, Ranthambhore, Dholpur, and adjoining areas (Singh et al. 2014; Khandal et al. 2020; Jhala et al. 2021). To estimate the number of potential male and female home ranges in this landscape, we divided the suitable Caracal habitat by the mean home range size derived from studies in semi-arid South African habitats (Appendix 5). As male and female home ranges vary substantially in size, with males typically occupying larger home ranges than females (Appendix 5), we performed these calculations separately for each sex. We estimated the mean home range and its associated uncertainty using non-parametric bootstrapping (10,000 resamples), and quantified uncertainty using percentile-based 95% confidence intervals derived from the bootstrap distribution of means.

RESULTS

Between January 2020 and March 2022, we deployed camera traps at 177 locations with a total survey effort of 5,258 camera trap days (Table 1). Our total study area encompassed ~600 km², of which ~450 km² was located inside Kailadevi Wildlife Sanctuary. We obtained a total of 92 independent photocaptures of the Caracal in 54 locations (Images 1–4).

Relative Abundance Index

The relative abundance index (RAI) of Caracal was highest in 2021 with a value of 2.113 (± 0.626) and lowest in 2022 with a value of 1.838 (± 0.541). There was no significant difference in RAI estimates between sessions (Kruskal–Wallis test: $H = 2.79$, $p = 0.247$, Table 1). In addition, we sighted Caracals on three occasions in 2020, on 12 occasions in 2021, and on seven occasions in 2022.

Habitat Suitability Modelling

The habitat suitability results indicated that out of the entire area of 109,663 km² spanning from eastern Rajasthan to western Madhya Pradesh, an area of 14,284 km² is suitable for the Caracal, of which about 26% lies within the protected area network (Table 2). About 1,230 km² of habitat was classified as highly suitable for the Caracal, of which 41% is distributed across the protected area network, with the Ranthambhore–Kailadevi–Dholpur cluster harbouring the largest contiguous patches (Figure 1).

Human footprint index and the presence of open natural ecosystems comprising open forests, grasslands, scrublands, and ravines contributed the most in predicting suitable Caracal habitat, followed by terrain ruggedness, distance from water, and distance from open natural ecosystem (ONE) (Figure 2). Open natural ecosystems influenced the probability of Caracal presence positively while increasing distance from open natural ecosystem reduced the probability, depicting the importance of these habitats for Caracal presence. The human footprint showed some tolerance towards human disturbance by Caracal. Terrain ruggedness index showed Caracal's positive response towards moderately rugged areas, however, highly rugged areas were not preferred by the species. Distance from water depicted the Caracal's positive response to proximity to water sources. The habitat suitability map also showed that

Table 1. Details of the survey effort, independent photocapture of the Caracal and relative abundance index in three sampling sessions in Kailadevi Wildlife Sanctuary, Rajasthan.

Year	Number of camera traps deployed	Total camera trap days	Average survey duration (range)	Number of camera trap locations where the Caracal was detected	Independent photo captures	Relative abundance index (SE)
January–March 2020	61	1,831	29.53 days (9–56 days)	22	35	2.025 (± 0.382)
January–March 2021	50	1,294	25.37 days (8–31 days)	14	20	2.113 (± 0.626)
December 2021–March 2022	66	2,133	32.21 days (11–44 days)	18	37	1.838 (± 0.541)
	177	5,258		54	92	



Images 1–4. Caracals photographed in Kailadevi Wildlife Sanctuary during the surveys. © Ranthambhore Forest Department.

Table 2. Details of habitat suitability classes modelled using the MaxEnt framework and their relative proportion within the protected area network.

Suitability category (Habitat suitability value)	Total area	Area inside protected areas	Area outside protected areas
Low (≤ 0.46)	8,571 km ²	1,969 km ² (22.97%)	6,602 km ² (77.03%)
Moderate (≤ 0.68)	4,486 km ²	1,224 km ² (27.28%)	3,262 km ² (72.72%)
High (≤ 0.91)	1,227 km ²	510 km ² (41.56%)	717 km ² (58.44%)
Total ($>0.2-\leq 0.91$)	14,284 km ²	3,703 km ² (25.92%)	10,581 km ² (74.08%)

Table 3. Details of the best fit model along with the contribution of each covariate and their level of significance used in the generalised linear model framework to determine site-specific influencing factors.

	Estimate	Standard error	z value	P(> z)
(Intercept)	-7.93	1.29	-6.171	6.77E-10
Availability of open natural ecosystems	2.86	0.862	3.319	0.000904
Distance from built-up area (remoteness)	0.000372	0.0000903	4.117	3.83E-05
Distance from water	-0.000164	0.0000794	-2.069	0.038515
Terrain ruggedness Index (TRI)	0.0225	0.00401	5.608	2.04E-08

a substantial amount of Caracal habitat was present outside the existing protected area network (Figure 1).

Factors influencing Caracal distribution

The GLM indicates that Caracal habitat use in the Kailadevi landscape increased in areas with greater ONE

cover and higher terrain ruggedness, closer proximity to water, and greater distance from built-up areas, underscoring a preference for open, rugged, and less human-disturbed habitats (Table 3). The area under ONE and ruggedness positively affected Caracal habitat

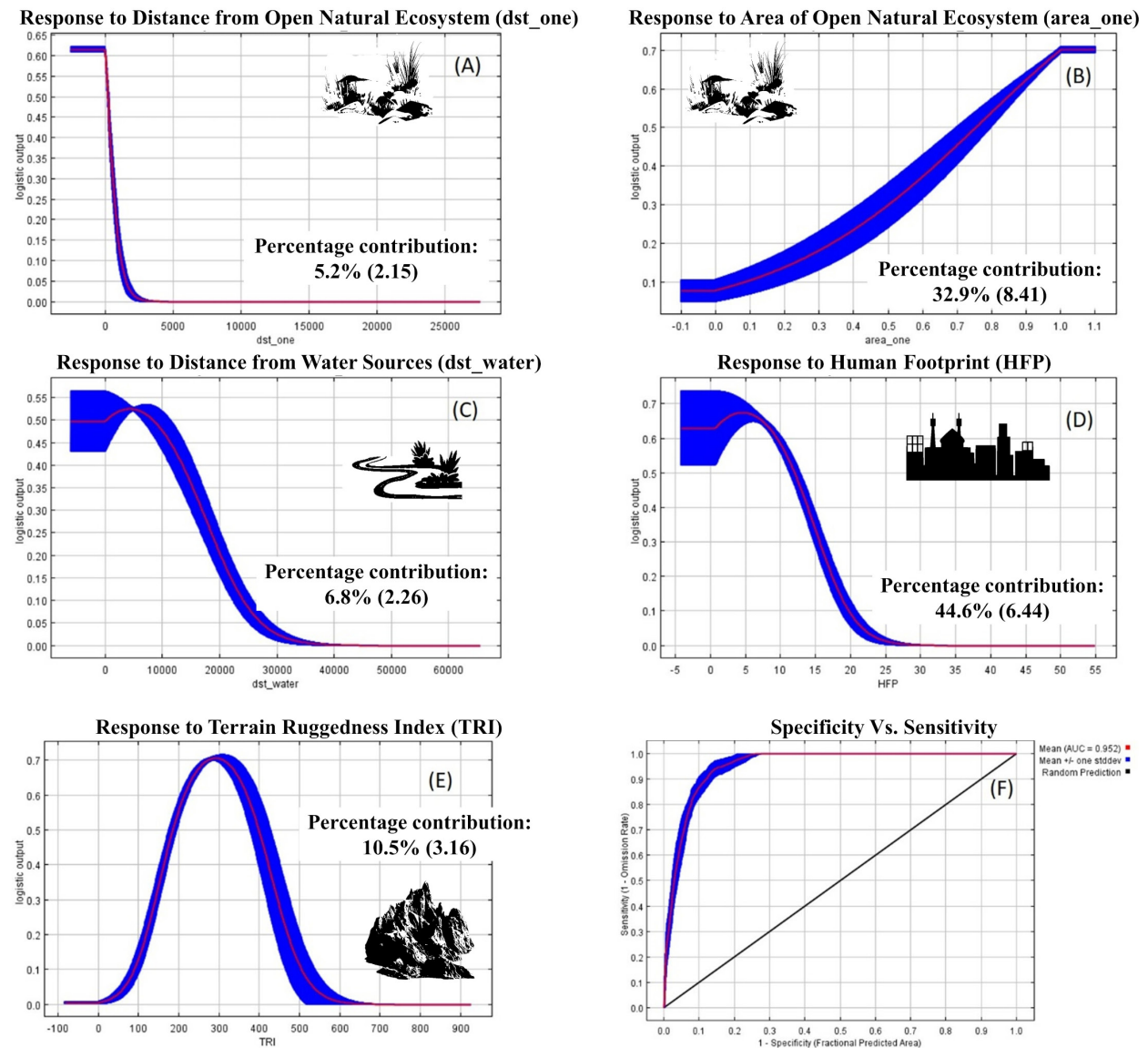


Figure 2. Response curves obtained from MaxEnt showing the relationship of different covariates with *Caracal* habitats: A—Distance from ONE | B—Area availability of ONE | C—Distance from water sources | D—Human foot print index | E—Terrain ruggedness index | F—Mean relation between sensitivity and specificity.

Table 4. Details of the site-wise estimates of potential number of *Caracal* home ranges derived from suitable habitat areas.

Site name	Suitable area	Number of male home ranges (range)	Number of female home ranges (range)	Total number of home ranges (range)
Ranthambhore	276.5 km ²	4 (2–11)	10 (6–24)	14 (8–35)
Kailadevi	639.18 km ²	8 (4–24)	23 (14–55)	31 (18–79)
Dholpur	192.69 km ²	3 (2–8)	7 (5–17)	10 (7–25)
Total	1108.37 km ²	15 (8–43)	40 (25–96)	55 (33–139)

use at the site level (Figure 3). *Caracal* used habitats closer to water bodies, with the probability of habitat use decreasing with increasing distance from water (Figure 3). Similarly, the probability of *Caracal* habitat use increased with greater distance from built-up areas (Figure 3), indicating higher use of areas with minimal human disturbance.

Potential Population Size

Our extrapolation indicates that the Ranthambhore–Kailadevi–Dholpur landscape can potentially accommodate 55 *Caracal* home ranges (CI_{95%} 33–139),

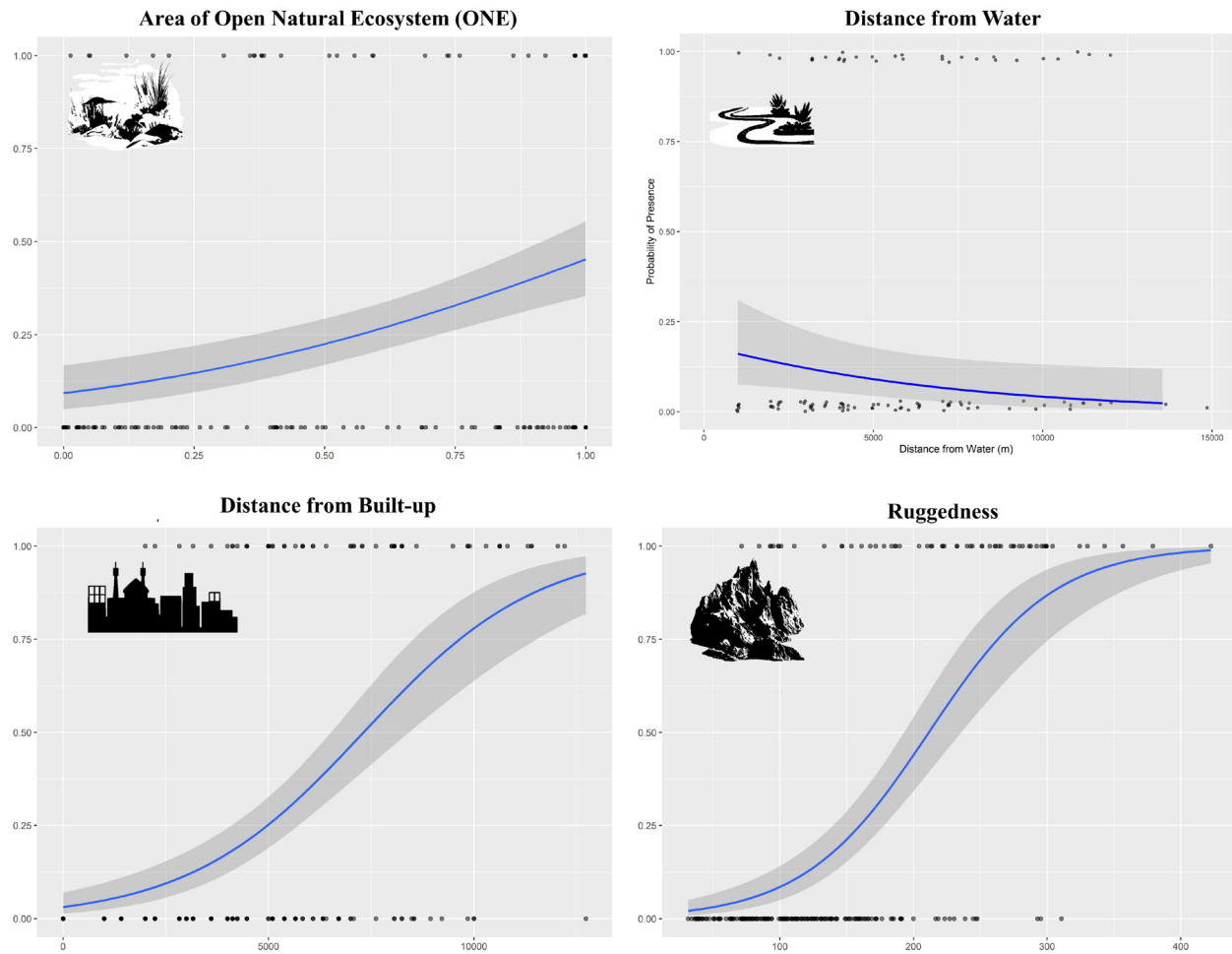


Figure 3. Factors influencing *Caracal* habitat use in the Kailadevi landscape, where availability of open natural ecosystems, distance from built up-area, and ruggedness show positive influence, while distance from water negatively influences *Caracal* habitat use.

including 15 male ($CI_{95\%}$ 8–43) and 40 female home ranges ($CI_{95\%}$ 25–96) (Table 4).

DISCUSSION

Our study in the Kailadevi landscape provides important insights into the distribution, abundance, and habitat use of the *Caracal* in a semi-arid ecosystem. The *Caracal* remains one of the least studied felids in India, and empirical information on its ecology, population status, and habitat associations remains limited. Using camera trap detections collected in the Kailadevi landscape, our study provides baseline ecological information on the *Caracal* and identifies key environmental and anthropogenic factors influencing its habitat use. These findings can help inform conservation planning to safeguard suitable habitats.

Relative Abundance Index and Potential Population Size

The RAI of *Caracal* recorded in the present study remained broadly consistent across the three sampling seasons. Although the mean RAI was lowest in the third year despite higher sampling effort, the confidence intervals overlapped across years, indicating no significant decline in the population trend. Similar inter-annual variation in relative abundance has also been reported in Ranthambhore National Park area, where *Caracal* RAI ranged 0.02–0.34 (Singh et al. 2014).

Obtaining reliable population estimates for low-density, wide-ranging species such as the *Caracal* is challenging; traditional population estimation methods, such as capture-recapture, distance sampling, occupancy modelling (mixture models), and total counts, are difficult to apply because of poor detectability and the lack of individually identifiable markings (Bookhout 1994). Information on abundance is often required by

management authorities to guide conservation planning (Nichols & Williams 2006). Our estimates indicate that Ranthambhore National Park could potentially harbour a smaller Caracal population than Kailadevi. Camera trap surveys in Ranthambhore National Park yielded a relatively low RAI for Caracal (Singh et al. 2014; Latafat et al. 2023) compared with Kailadevi Wildlife Sanctuary (Table 1). While Ranthambhore National Park is largely characterized by *Anogeissus*-dominated woodlands with some mesic savanna patches, the Kailadevi landscape represents a more heterogeneous ecosystem, ranging from dense forest in narrow valleys to treeless scrublands and grasslands on plateau tops, often degraded due to prolonged anthropogenic pressure (Yadav 2022). Furthermore, Ranthambhore National Park supports high Tiger and Leopard population densities (Sadhu et al. 2017; Qureshi et al. 2024), which may influence Caracal abundance and detection through intraguild interactions or spatial avoidance (Davis et al. 2023). Our relative abundance estimates fall within the range reported in other parts of the Caracal's distribution, although considerable variation exists across landscapes. Studies in parts of the Arabian Peninsula and western Asia yielded higher encounter rates (Khorozyan et al. 2014; İlemin et al. 2023) than our estimates. The Caracal's low-density occurrence in our study area may be attributable to the circumstance that this area lies on the eastern edge of the global distribution of the Caracal, which may contribute to its inherently low-density occurrence in this region (McGill & Collins 2003).

The home range based population approximation presented here should be viewed primarily as a baseline for understanding the potential conservation significance of the Kailadevi–Ranthambhore–Dholpur landscape. This approach assumes uniform habitat quality across the landscape and non-overlapping home ranges within the identified suitable areas, which is rarely true in natural ecosystems. In addition, due to the lack of empirical home range estimates in Indian semi-arid ecosystems, we relied on values reported in semi-arid South African study areas. However, we omitted mean home range estimates for Caracals generated in arid savanna and steppe desert ecosystems, as these are larger than in semi-arid habitats (Bothma & Le Riche 1994; Van Heezik & Seddon 1998; Marker & Dickman 2005). Although derived from suitable habitat extent and published home range estimates, such approximations provide a useful starting point for guiding conservation planning and prioritising areas for monitoring and habitat management.

Habitat Suitability Modelling

The habitat suitability modelling indicates that potentially suitable habitat for the Caracal occurs in and around the Greater Ranthambhore ecosystem and Sariska landscape (Figure 1). These areas occur as relatively restricted pockets within the landscape. About 26% of this suitable habitat falls within the existing protected area network. Hence, a substantial proportion of potential Caracal habitat lies in multiple-use landscapes outside formally protected areas. This pattern highlights the importance of non-protected landscapes in sustaining a Caracal population and underscores the potential role of habitat connectivity across the broader landscape.

The habitat suitability model indicates that the presence of open natural ecosystems, distance from human settlements, and terrain ruggedness significantly influence Caracal habitat use in the landscape. The positive association with open natural ecosystems and terrain ruggedness in our model parallels patterns reported from arid and semi-arid systems in Iran and the Arabian Peninsula (Khosravi et al. 2018; Dunford et al. 2024; Jamali et al. 2024). Conversely, as the distance from ONE habitat increases, the probability of detecting Caracal declines, indicating decreasing habitat suitability. Similar observations of Caracal preferring open habitats over dense vegetation cover have also been reported in Sub-Saharan Africa and parts of western Asia (Hanekom & Randall 2015; Davis et al. 2023; İlemin et al. 2023).

Terrain ruggedness also emerged as a key factor influencing the distribution of Caracal. In our study area, rugged open natural ecosystems largely correspond to the ravines of the Chambal River and its tributaries, which form an intricate network of gullies across the landscape. These ravines function as important refuge habitats for several wildlife species, including Caracal (Sadhu 2020). The structural complexity and relative inaccessibility of these ravine systems may provide suitable hunting grounds as well as protection from human disturbance. Consequently, these findings suggest that conservation strategies should prioritise safeguarding the ravine habitats that may offer optimal ecological conditions for the persistence of Caracal populations.

The bell-shaped response curve for distance from human settlements highlights the Caracal's moderate tolerance to human activities. Caracals inhabiting multi-use landscapes often coexist with human presence but tend to prefer habitats that minimize direct encounters with people (Ünal et al. 2020). Our results indicate that while Caracals may adapt to low to moderate levels of

human presence, densely populated areas could pose significant threats. Such patterns are consistent with findings on other medium-sized felids. For example, the Jungle Cat also persists within fragmented but suitable habitat mosaics in human-modified landscapes (Mukherjee & Nandini 2024, Ganguly et al. 2026).

Distance from water sources emerged as a notable factor influencing habitat suitability in the study area, although its relative contribution was lower compared to other predictors. Caracals were more likely to occur closer to water sources, a pattern consistent with observations of carnivores in arid ecosystems where water scarcity can strongly shape habitat use (Ramesh et al. 2017; Hadad et al. 2025). Although the Caracal is adapted to dry conditions, the presence of small water bodies such as seasonal streams or lakes can be important for sustaining both the species and its prey base (Dunford et al. 2024).

Generalised Linear Modelling

The Generalized Linear Model identified availability of open natural ecosystems, terrain ruggedness, distance from built-up areas, and proximity to water sources as significant predictors of Caracal detections at camera trap sites within the Kailadevi landscape. The positive association with open natural ecosystems highlights the importance of structurally open habitats that support key prey such as hares, rodents, and ground-dwelling birds (Mukherjee et al. 2004; Ramesh et al. 2017). Terrain ruggedness also emerged as a strong determinant of site use; in Kailadevi, such conditions are largely represented by the ravine systems of the Chambal River and its tributaries (Yadav 2022) and may provide denning opportunities, concealment cover, and refuge from predators or human disturbance (Ayan Sadhu, pers. obs.). Caracal detections increased with greater distance from built-up areas, indicating avoidance of human settlements, and suggesting that the species persists in human-dominated landscapes by preferentially using relatively undisturbed habitats. Distance from water sources also significantly influenced detections, with higher probabilities of occurrence closer to water bodies; although the Caracal is adapted to semi-arid environments, water availability can indirectly shape carnivore distribution by sustaining prey populations in dry landscapes (Ramesh et al. 2017).

Collectively, these results indicate that Caracal habitat use at the camera trap scale in Kailadevi is governed by a combination of habitat structure and anthropogenic pressures, underscoring the need to safeguard open natural ecosystems and ravine habitats

that function as key refugia for the species within this human-dominated landscape.

A caveat of our study is that Caracal photocaptures were obtained as by-catch from camera traps deployed primarily for monitoring the Tiger. Therefore, camera trap placement was optimised for large carnivores rather than small cats, which may introduce sampling bias. However, our analysis is limited to broad habitat associations based on detection locations and does not attempt to estimate population density or detection-corrected occupancy. Our findings highlight the importance of open natural ecosystems and structurally complex habitats within the Kailadevi landscape for the Caracal.

Given the limited ecological information currently available for the Caracal in India, systematic and dedicated surveys across its potential range are necessary to improve understanding of its distribution and to identify areas that may support viable population units. Such efforts would help refine current knowledge on habitat associations and inform landscape-level conservation planning. As a considerable proportion of suitable habitats occurs outside legally designated protected areas, conservation strategies should also focus on safeguarding these ecologically significant but administratively unprotected landscapes. Rather than expanding conventional protected area frameworks, efforts should aim to maintain the ecological character of these open natural ecosystems while supporting sustainable land-use practices. Promoting livelihood options compatible with biodiversity conservation, such as sustainable grazing, low-intensity agriculture, and community-based monitoring initiatives, may help maintain habitat quality while supporting the needs of local communities (Sircely et al. 2022). At the same time, preventing the conversion of these habitats into intensive land uses such as large-scale mining, industrial development, or other forms of high-impact land transformation will be important for retaining suitable habitats for the Caracal. Finally, while the camera trap-based results presented here provide valuable baseline information, further research, particularly fine-scale resource selection, would improve understanding of Caracal movement patterns, resource selection, and seasonal space use in human-dominated semi-arid landscapes.

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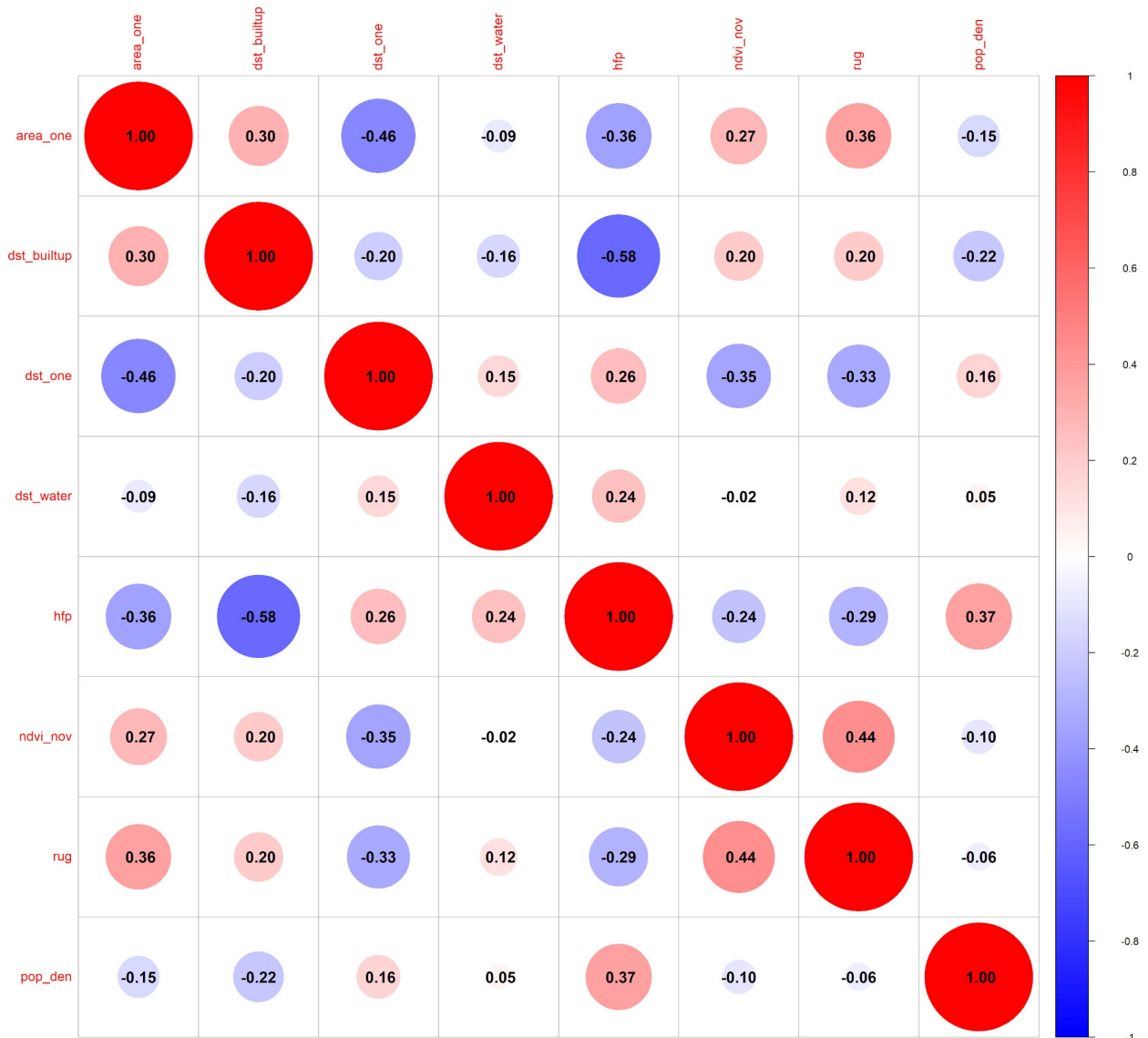
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Appendix 1. Covariates used for predicting *Caracal* suitable habitat and habitat use in the study area.

Environmental variable	Resolution	Ecological justification	Source
Terrain ruggedness index (TRI)	30 m	Rugged areas in the landscape provides apt opportunity for the <i>Caracal</i> to take refuge during the day while foraging in the human-dominated landscape at night.	Farr et al. 2007
Human foot print index (HFP)	1,000 m	The <i>Caracal</i> is tolerant towards human disturbance to some extent, but avoids a higher degree of human disturbance	Mu et al. 2022
Built-up	10 m		Karra et al. 2021
Water source	30 m	In semi-arid landscapes, water is the key limiting factor, therefore, proximity to water source shall act as a major driving factor	Pekel et al. 2016
Open natural ecosystem (ONE)	30 m	The <i>Caracal</i> is known to inhabit open forest ecosystems, therefore, the ONE should positively influence its distribution	Madhusudan & Vanak 2023
Normalized difference degetation index (NDVI; for November)	30 m	NDVI reflects vegetation productivity and habitat quality, which influence prey availability and cover.	Derived from Landsat 8 satellite data images https://earthexplorer.usgs.gov/

Appendix 2. Correlogram showing relationships between different covariates used for the habitat suitability analysis.



Appendix 3. Table depicting different models used for modeling suitable habitat of the Caracal in the Greater Ranthambhore Ecosystem, with area under the receiver operating characteristic curve (AUC) and different model settings. All model combinations were replicated 100 times using the bootstrap type. Human footprint (HFP) | Terrain ruggedness index (TRI) | Area of open natural ecosystem (Area_ONE) | Distance to open natural ecosystems (Dst_ONE) | Distance to water (Dst_water) | Normalized difference vegetation index for November (NDVI_Nov) | Distance to built-up areas (dst_builtup).

Model combination	AUC	Model settings	Test data	Output format
HFP+ TRI+ Area_ONE+ dst_ONE+ dst_water	0.952	Linear + Quadratic + Product	20%	Logistics
NDVI_Nov+ Area_ONE+ TRI+ dst_water+ dst_one+ dst_builtup	0.941	Linear + Quadratic + Product	20%	Logistics
HFP + Dst_One+ TRI+ dst_builtup+ dst_water+ NDVI_Nov	0.917	Linear + Quadratic + Product	20%	Logistics
hfp+ dst_builtup+ dst_ONE+ ndvi_nov	0.915	Linear + Quadratic	20%	Logistics
hfp+ area_one+ dst_one	0.859	Linear + Quadratic + Product	20%	Cloglog

Appendix 4. Different models used in the generalised linear model framework to determine site-specific factors influencing Caracal habitat use in the semi-arid western Indian landscape. The best fit model glm3 was determined by the lowest AICc value. Terrain ruggedness index (TRI) | Open natural ecosystem (ONE) | Normalized difference vegetation index for November (NDVI) | Human footprint (HF) | Degrees of freedom (df) | Akaike information criterion (AICc) with correction for small sample size (Δ AICc).

	Intercept	Area ONE	Distance to built-up areas	TRI	Distance to water	Distance to ONE	NDVI	HF	df [^]	AIC _c	Δ AIC _c	AIC _c weight
glm3	-7.932	2.862	0.000372	0.02251	-1.64E-04				5	144.3	0	0.71
glm2	-7.733	2.225	0.000311	0.02061					4	146.8	2.5	0.203
glm6	-3.103	2.838		0.01894	-1.60E-04			-0.154	5	149.0	4.76	0.066
glm5	-3.828	2.15		0.01783				-0.1176	4	151.7	7.47	0.017
glm11	-5.779		0.00034	0.01784					3	155.5	11.22	0.003
glm12	-5.576		0.000364	0.01809	-6.46E-05				4	156.7	12.41	0.001
glm4	-6.601			0.02026	9.19E-06	-0.00149	13.41		5	164.4	20.12	0
glm10	0.6702	1.504			-1.25E-04		6.724	-0.2212	5	176.4	32.1	0
glm7	3.356				-1.17E-04	-0.00085		-0.2266	4	177.1	32.79	0
glm8	-2.579		0.000428		-4.76E-05	-0.00092			4	192.4	48.09	0
glm9	-3.799	1.437	0.000443		-7.28E-05				4	193.9	49.58	0

Appendix 5. Home range estimates of radio-collared Caracals in semi-arid South African study areas.

Study area	Age class and sex	Home range size (km ²)	Fixes	Source
Stellenbosch Mountains, Cape Province	Young male	65	25	Norton & Lawson (1985)
Postberg Nature Reserve, West Coast National Park	Young male	27.5	298	Avenant & Nel (1998)
	Adult male	26.44	352	
	Young female	5.59	52	
	Adult female	8.91	558	
Agricultural landscape, Drakensberg Midlands, KwaZulu-Natal Province	Young female	7.66	375	Ramesh et al. (2017)
	Adult male	243.1	1349	
	Young female	25.88	1291	
	Adult female	64.38	1501	
	Young female	79.08	507	
	Adult female	6.96	1501	
	Adult female	26.39	1464	

Home range size based on non-parametric bootstrapping with 10,000 iterations

Sex	Average	Standard error	Lower limit	Upper limit
Male	90.71816	44.9277	26.97	189.2
Female	28.07304	9.333559	11.65	47.36

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Articles

Large mammal diversity of Vietnam's Chu Yang Sin National Park and the first experimental assessment of their vulnerability to snaring
– Minh Thi Anh Nguyen, Thuy Thi Bich Vo, Quy Tan Le, Vy Tran Nguyen, Vu Linh Nguyen, R.J. Timmins & Anthony J. Giordano, Pp. 28739–28749

Rapid camera-trap assessment of mammals in Tripura, India: new records and implications for conservation
– Omkar Patil, Ashutosh Joshi, Rutuja Digaskar & Amey Parkar, Pp. 28750–28769

Distribution, habitat use, and abundance of the Caracal *Caracal caracal* (Schreber, 1776) (Mammalia: Carnivora: Felidae) in a semi-arid Indian landscape
– Mohammad Mairaj, Dhruv Jain, Ramanand Bhakar & Ayan Sadhu, Pp. 28770–28783

Avian richness and habitat selection patterns in Jhimil Jheel Conservation Reserve, Uttarakhand, India
– Ankita Das, Soumya Dasgupta & Ramesh Krishnamurthy, Pp. 28784–28806

Herpetofauna of the Chitwan-Annapurna Landscape, Nepal: a comprehensive species checklist including occurrence in protected areas, with suggested conservation recommendations
– Santosh Bhattarai, Bishal Prasad Neupane, Bivek Gautam, Prabin Shrestha, Ashley R. Olson, Fiona Hogan & Wendy Wright, Pp. 28807–28829

Dietary assessment of tadpoles of selected rhacophorid frogs (*Polypedates*, *Rhacophorus*, *Zhangixalus*) (Amphibia: Anura: Rhacophoridae) of Kangchup, Manipur, India
– Yumkham Shelina Devi & Saibal Sengupta, Pp. 28830–28837

Eastern range record of the semiaquatic freshwater earthworm *Glyphidrilus gangeticus* Gates, 1958 (Clitellata: Crassicitellata: Almidae) from West Bengal, India, with a brief key to the Indian species of the genus
– M. Nurul Hasan, John Warren Reynolds, Hasko F. Nesemann, Shyamasree Ghosh & Chandra Kanta Mandal, Pp. 28838–28844

Succession of biofouling organisms on structural materials and their environmental drivers off the Kalpakkam coast, India
– Bandita Badakumar, D. Inbakandan & P. Sriyutha Murthy, Pp. 28845–28861

Addition of five lesser known angiosperm species from Mizoram, India
– R. Lalthantluanga, Dorothy Lalbiakhluni, Vanlalawmpuia Sailo, Rose Laldinaii Darnei, R. Lalhruaitluangi, Sanatombi Devi Yumkham & Sandhyarani Devi Khomdram, Pp. 28862–28873

Legislative and evidentiary challenges faced by the Indian law enforcement agencies in social media-enabled wildlife offences
– Pradipty Bhardwaj, Jayadevan S. Nair & H.V. Girisha, Pp. 28874–28885

Communications

Occurrence and prevalence of gastrointestinal parasites in herbivores in Dampa Tiger Reserve, Mizoram, India
– G.S. Solanki, Lalrinkimi & Phoebe Lalremruati, Pp. 28886–28893

Theileriosis in a captive Indian Gaur *Bos gaurus*: a rare encounter
– Kaushal Kumar, Vishal Kumar Sinha, Deepak Kumar, Imran Ali, Ramesh Tiwary, Pankaj Kumar & Amit Kumar, Pp. 28894–28899

Avifaunal diversity in agroecosystems: a case study from Uttar Pradesh, India
– Fatima Khan & Kaleem Ahmed, Pp. 28900–28910

First record of the Sistan Sand Boa *Eryx sistansensis* Eskandarzadeh et al., 2020 (Reptilia: Serpentes: Erycidae) from India
– Vivek Sharma & Dharmendra Khandal, Pp. 28911–28918

Population dynamics and habitat assessment of Indian Flapshell Turtle *Lissemys punctata vittata* (Reptilia: Testudines: Trionychidae) in Chawandiya, Rajasthan, India
– Mahaveer Prasad Vaishnav & Amol Arora, Pp. 28919–28925

A preliminary checklist of dragonflies and damselflies (Insecta: Odonata) of Kanyakumari District, Tamil Nadu, India
– V. Muthukrishnan, Anand Shibu, Vinod Sadhasivan & R. Amirtha Balan, Pp. 28926–28939

Documentation of dicotyledonous angiosperm diversity of Kanakamala, Kerala, India
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Diversity of dye-yielding plants traditionally used by ethnic communities of Assam, India
– Bhuvan Chandra Chutia, Hena Parbin, Abhijit Chandra Roy, Krishna Kanta Medhi & Utpal Bora, Pp. 28950–28956

Review

Ichthyofaunal diversity and conservation status of Nagaland, India: a comprehensive review
– Rejuba Pongen & Pranay Punj Pankaj, Pp. 28957–28970

Short Communications

Preliminary observations on the breeding ecology and potential threats to Bonelli's Eagle *Aquila fasciata* in Sithagiri Malai, Tamil Nadu, India
– S. Naveenkumar, H. Byju & H. Maitreyi, Pp. 28971–28975

A nesting attempt by Greater Flamingo *Phoenicopterus roseus* in an inland wetland in Kachch District, Gujarat, India
– Gaurav Sirola, Harindra Baraiya, Rajdeep Mitra, Anju Baroth & R. Suresh Kumar, Pp. 28976–28981

First time in 110 years: sighting of *Gynacantha khasiaca* MacLachlan, 1896 (Odonata: Aeshnidae) in Arunachal Pradesh, India
– R. Mahesh, Rajesh Gopinath, Gaurav Joshi & Roshan Upadhaya, Pp. 28982–28987

Notes

Evidence of Rusty-spotted Cat *Prionailurus rubiginosus* (I. Geoffroy Saint-Hilaire, 1831) (Mammalia: Carnivora: Felidae) in National Chambal Sanctuary, Uttar Pradesh, India
– Anshoo Nishad, Hiyashri Sarma, Rajib Saha, Vijay Pratap Singh, Maneesha Bhatt, Atit Rai, Qamar Qureshi & Vishnupriya Kolipakam, Pp. 28988–28990

First photographic record of Naumann's Thrush *Turdus naumanni* Temminck, 1820 from Assam, India
– Pulakeswar Basumatary, Pp. 28991–28994

New breeding record of Black-headed Ibis *Threskiornis melanocephalus* from Malappuram District, Kerala, India
– K.K. Junaina & A.P. Rashiba, Pp. 28995–28997

From the heart of Urad: records of *Cyrtodactylus bapme* Kamei & Mahony, 2021 (Reptilia: Squamata: Gekkonidae) from Assam, India, with comments on the pre-loocal region in males
– Manmath Bharali, Pranjal Swargiary, Tejas Mariswamy, Madhurima Das, Jayaditya Purkayastha & Sanath Chandra Bohra, Pp. 28998–29002

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