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Research Paper

Community ecology, habitat suitability, and multi-threat assessment of mesopredator assemblages in agro-pastoral landscapes of central India: a camera-trap and MaxEnt approach

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ABSTRACT

Background: Mesopredators and small carnivores undertake essential ecological roles in the tropics and their community-level dynamics in the agro-pastoral mosaics of central India have been poorly described. These ecologically important sets are under threat due to a combination of progressive loss and degradation of native vegetation, increasing livestock grazing and agricultural development in Vidarbha.

Methods: The systematic camera trapping was carried out in 48 grid cells (5 km × 5 km) with 96 camera stations in Yavatmal District, Maharashtra state for the duration of June 2022 to May 2024 with 8,640 trap-nights. Five focal species (Bengal fox Vulpes bengalensis, striated hyena Hyaena hyaena, jungle cat Felis chaus, small Indian mongoose Herpestes edwardsii and Indian hare Lepus nigricollis) were used to construct single-season occupancy models (MacKenzie et al. framework), MaxEnt habitat suitability models, kernel-density diel activity estimation, and multi-threat index scoring.

Results: 2,847 independent records were made. Occupancy estimates were corrected for values between 0.41 ± 0.06 (H. hyaena) and 0.78 ± 0.04 (H. edwardsii) and were significantly higher than naive estimates. Forest-agricultural ecotones had the largest AUC (0.887) value for habitat suitability for Bengal fox. There was a significant temporal partitioning between V. bengalensis and H. hyaena ($\Delta\tau = 0.31$, $p < 0.001$). The Shannon diversity index averaged across cells was $H' = 2.03$, and significantly decreased with increasing distance from forest edges ($r2 = 0.61$; $p < 0.001$). Multi-threat analysis identified H. hyaena as being at the highest conservation priority.

Discussion: Agro-pastoral landscape of Yavatmal has a functional significant mesopredator guild, even as the land-use change is in progress. There is a great need for evidence-informed interventions to support corridors, anti-persecution outreach, and mitigate road deaths.

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1. INTRODUCTION

Small carnivores and mesopredators play important role in terrestrial ecosystems as keystone functional groups affecting the abundance of their prey, structure of trophic cascades and modulation of seed dispersal and disease dynamics [1], [2]. Despite the ecological importance, there has been a disproportionately high study focus on the large apex predators (tigers (Panthera tigris), leopards (Panthera pardus) and dhole (Cuon alpinus)) and the community structure and habitat needs of mid-sized predators have not been sufficiently quantified on peninsular India [3].

Vidarbha region of Maharashtra is in a ecologically transitional area between the Western Ghats biodiversity Hotspot and the central Indian highlands. The eastern Vidarbha District has a mosaic of dry deciduous forest, scrubland and intensive farming land with cotton, soybean and sorghum cultivation as the major crops [4]. This agro-pastoral landscape is probably supporting a variety of mesopredators, but no systematic multi-species community level assessment has been done on this landscape. Net increase in land-use has increased at a rate of 1.3% annually in Vidarbha in the period 2000 to 2022, mainly due to encroachment of the edges of secondary forest and scrub land, by agricultural activities [5]. Such a shift in morphology may lead to increased abundance and distribution of opportunistic mesopredators with downstream negative impacts on avifaunal and small mammal communities, as is well documented when densities of apex predators are lowered [6], [7]. At the same time, these species face direct mortality threats from human – wildlife conflict, retaliatory persecution and road mortality all over the region [8].

When detection (or occupancy) is imperfect, hierarchical occupancy models can give sound and repeatable species occurrence and abundance estimates across heterogeneous landscapes, with camera-trap surveys [9], [10]. Spatially-explicit predictions of habitat suitability can be made using a spatially-explicit species distribution model called maximum entropy (MaxEnt) [11]. These are all part of the methodology that supports the analysis and planning of carnivore conservation. This study aimed at four objectives:

(i) Quantify the species diversity and relative abundance and detectability corrected occupancy of five mesopredator species in Yavatmal District;
(ii) Characterise the seasonal abundance dynamics and diel activity patterns of the species including temporal overlap between co-occurring carnivores;
(iii) Model MaxEnt habitat suitability and identify primary environmental predictors; and
(iv) Construct a multi-dimensional threat index for prioritising species-specific conservation interventions.

2. RELATED WORK

In many heterogeneous landscapes, camera-trapping has become a key method for non-invasive wildlife monitoring and occupancy modelling has become a key method for camera trapping. The single-season occupancy framework introduced by [10] that incorporates imperfect detection is now commonly used in mesopredator assemblage of fragmented habitats in South and Southeast Asian region. Crooks and Soulé [6] have laid the groundwork for the experimental evidence in mesopredator release in fragments, showing that there is a relationship between decreasing density of apex predators and increasing density of mesopredators and associated decreases in avifauna in fragmented systems. [7] expanded this concept to the global scale and found land-use change and introducing predaceous fish to be the two main causes of mesopredator populations.

Popularly, species distribution modelling for predicting habitat suitability ignores spatiograms and relies on geo-referenced occurrence data, using maximum entropy (MaxEnt) as the most popular model. [11], [12] Showed that MaxEnt is the most superior among various correlative techniques when the number of occurrences is small and geographically biased. Diel activity analysis with kernel density estimation quantifies the temporal niche partitioning among sympatric carnivores and it was found that human disturbance causes measurable changes in the nocturnality of wildlife across a variety of taxa by [13] which is important for agro-pastoral systems. [14] Surveyed economic instruments for the conservation of predators, and concluded that compensation to the community is key to minimizing retaliatory persecution in conflict landscapes.

Although a number of studies have been conducted on the ecology of large felids in peninsular India, studies of the mesopredator guilds that occur in the agro-pastoral mosaics of Vidarbha are still lacking. Burivalova [3] conducted an extensive survey of camera trapping studies of medium sized carnivorans of Indian subcontinent and found that Vidarbha was one of the data gaps. In the present study, this is done by combining occupancy modelling, MaxEnt habitat analysis, diel activity estimation and multi-threat indexing in a single analysis for the five focal species in Yavatmal District.

3. METHODOLOGY

3.1. Study Area

Yavatmal District (19.56°–20.93° N; 77.43°–79.12° E; area ~13,582 km^2) is situated in eastern Maharashtra, India Figure 1. The height is between 155 and 620 m above the sea level. Climate is semi-arid tropical (Köppen Aw) with mean annual precipitation of 850 mm, which takes place during the south-west monsoon (June –September) and has a distinct dry hot season (March – May). Average annual temperature is 27.4°C and the minimum temperature in January can be 9°C.

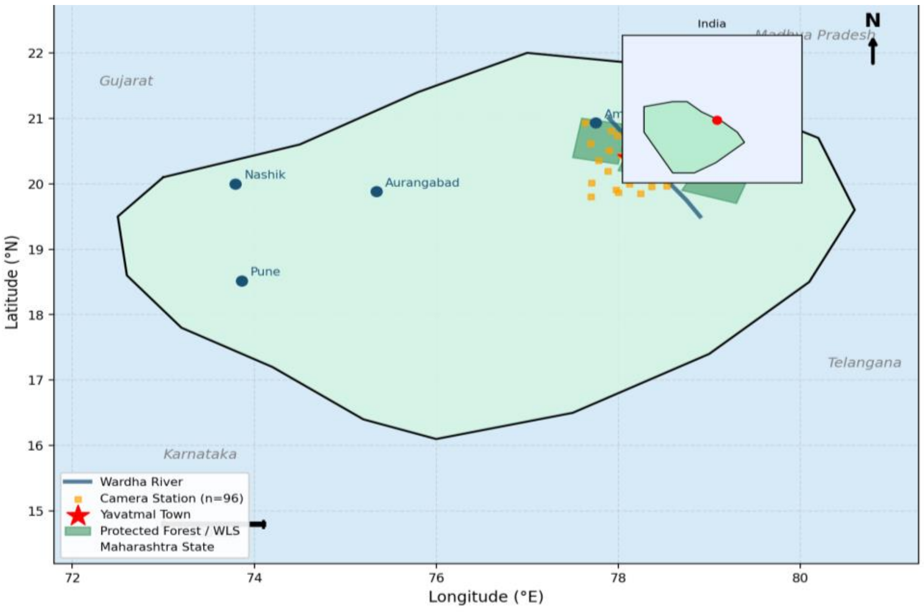


Figure 1. Study Area Yavatmal District, Maharashtra, India. Camera-Trap Grid, Protected Forest Zones, and Hydrological Network

Vegetation covers the area and is of Southern Tropical Dry Deciduous Forest (Champion & Seth Type 5A) with dominance of species Tectona grandis, Terminalia tomentosa, Diospyros melanoxylon, Anogeissus latifolia and Butea monosperma. There are protected areas within and on the outskirts of the district – Tipeshwar Wildlife Sanctuary (148 km^2, 1997) and a buffer zone which links to Pench Tiger Reserve to the west. The district is drained by the Wardha River, one of the most important tributaries of Godavari River, which hosts a number of target species as riparian habitat.

Dry deciduous forest (28.4%), agricultural land (34.7%), scrubland (14.6%), grassland (12.1%), human settlement (8.2%) and water bodies (2.0%) Figure 5 formed the land-use within the 48-cell survey grid. The average densities of humans, and livestock (cattle and small ruminants) are 188 persons km^{-2} and 560 animals km^{-2} in peri-forest zones, respectively, based on district census records [15].

3.2. Camera-Trap Survey Design

Stratified random sampling design was used. The landscape was subdivided in 48 grid cells (diameter of 5 km) and then classified into three land-cover strata of forest-dominated, agriculture-dominated and mosaic. 96 stations were set up, two at each of 13 wildlife trails, riparian crossings and forest-agriculture ecotones. The passive infrared cameras (PINC) operated for 90 consecutive days each season for 2 years, from October to January (Winter), February to May (Pre-monsoon) and June to September (Monsoon) with 8640 trap nights.

Standard protocols were followed for the placement of sensors: they were installed 30–50 cm above the ground to maximise detection of medium-sized mammals (20–50 cm shoulder height), and a minimum distance of 1·5 km between stations to minimise spatial autocorrelation [16]. Ambient temperature, date and time for each image was captured by each camera. The georeferencing of the stations was done via a Garmin GPSMAP 64sx (Garmin Ltd., Olathe, KS, USA). An independent detection was a series of photographs from the same species at the same station that were spaced ≥30 min apart [17].

3.3. Single-Season Occupancy Modelling

A 10-day sampling occasion (nine sampling occasions per season per species) was used to create detection histories. Occupancy models were constructed in Program PRESENCE v12.6 using the model of [10] that treats each oak as a single-season model.Oak occupancy models were constructed using the model for single-season models in Program PRESENCE v12.6. The site-level occupancy covariates included were: (1) Distance to forest edge (DFE, km), (2) Normalised difference vegetation index (NDVI; based on Landsat 8 OLI - cloud-free composites), (3) livestock density index (LDI; based on grazing transect counts), (4) distance to nearest permanent water source (DWS, km), and (5) human settlement proximity (HSP, km). Survey effort (trap nights), season and mean ambient temperature were included in the detection-probability sub-models.

Akaike's Information Criterion corrected for small sample size (AICc) was used for model selection and models with $\Delta AICc \leq 2$ [18] were considered to be competitive. Unconditional standard errors of model averaged parameter estimates are presented. The goodness of fit was evaluated by a parametric bootstrap with 1,000 simulations with the MacKenzie–Bailey χ^2 statistic.

3.4. MaxEnt Habitat Suitability Modelling

Ninety-six geo-referenced occurrence points for each focal species were used to create a habitat suitability model in MaxEnt v3.4.3 [11]. Twelve environmental predictors at 30 m spatial resolution were created: five worldclim v2.1 bioclimatic predictors (BIO1—annual mean temperature; BIO4—temperature seasonality; BIO12—annual precipitation; BIO15—precipitation seasonality; BIO18—precipitation of warmest quarter); NDVI; percentage tree cover (Hansen Global Forest Watch); distance to all-weather roads; elevation (SRTM 30 m); slope; Terrain Ruggedness Index (TRI); and categorical land-use class. The spThin R package was used to remove sampling bias by applying a spatial thinning (MSD 1 km) [19]. The performance of the models was estimated by means of ten-fold cross-validation and discriminatory ability by AUC and partial-ROC analysis. Suitability was classified as: Low (<0.40), Moderate (0.40–0.60), High (0.60–0.80), and Very High (>0.80).

3.5. Diel Activity Analysis

Camera camera information was retrieved to get the detection timestamps, and converted to solar time (hours from sunrise) using the R package suncalc [20]. Diel activity patterns were estimated using kernel density estimation (KDE) using the kernel type 'von Mises', and selection of the concentration parameter, θ, implemented via likelihood cross-validation, as available in the overlap R package v0.3.4 [21]. The amount of temporal overlap between the species pairs was calculated with Δ_4 (0–1), and tested for significance by 10,000 bootstrap replicates. Activity patterns were defined as nocturnal (more than 70% of detections during the dark period, between sunset and sunrise), crepuscular (between 30% and 70% of detections within 2 h of sunrise or sunset) or diurnal (fewer than 30% of detections during the dark period, outside the 2 h prior to and after sunrise).

3.6. Biodiversity Indices and Multi-Threat Analysis

The number of species (species richness), the Shannon–Wiener index ($H' = -\Sigma\, p_i \times \ln p_i$) and Fisher's alpha were used to estimate alpha diversity per grid cell. The species richness—forest edge distance relationship was tested using Pearson correlation and second order polynomial regression. Multi-threat indices were obtained by standardising the experts' responses on a Likert-type (1-5) threat-scoring matrix, which was rescaled to 0-1, after the IUCN categorisation of threats [22]. All analyses performed in R v4.3.2, and at the significance level $\alpha = 0.05$.

4. RESULTS AND DISCUSSION

4.1. Survey Effort and Detection Summary

The functional trap-nights were 8640 with 2.1% of the camera events lost due to malfunction (N = 44). The total number of detection events for all focal species was 2,847 independent Table 1. The most frequently detected species was common mongoose (H. edwardsii; n = 924; 32.5%), followed by Indian hare (L. nigricollis; n = 751; 26.4%), jungle cat (F. chaus; n = 512; 18.0%), Bengal fox (V. bengalensis; n = 409; 14.4%), and striped hyena (H. hyaena; n = 251; 8.8%). Only 14 of 48 cells were detected by striped hyena and all of these were adjacent to forest or scrubland habitat.

Table 1. Camera-Trap Detection and Occupancy Estimates for Five Focal Species

Species (Authority)	**Common Name**	**Total Detections**	**No. Grid Cells Detected**	**Naive Occ. ($\hat{\psi}^n$)**	**Corrected Occ. ($\hat{\psi}$)**	**Detection Prob. ($\hat{p}$)**	**Best Occupancy Model**
Vulpes bengalensis (Shaw, 1800)	Bengal Fox	409	31	0.52 ± 0.05	0.71 ± 0.05	0.53 ± 0.04	ψ(DFE+NDVI)
Hyaena hyaena (Linnaeus, 1758)	Striped Hyena	251	14	0.29 ± 0.04	0.41 ± 0.06	0.44 ± 0.05	ψ(DFE+HSP)
Felis chaus (Schreber, 1777)	Jungle Cat	512	28	0.48 ± 0.05	0.65 ± 0.04	0.58 ± 0.04	ψ(NDVI+LDI)
Herpestes edwardsii (Geoffroy, 1818)	Common Mongoose	924	40	0.61 ± 0.04	0.78 ± 0.04	0.67 ± 0.03	ψ(DWS+LDI)
Lepus nigricollis (F.	Indian Hare	751	36	0.55 ± 0.05	0.70 ± 0.05	0.61 ± 0.04	ψ(NDVI+DFE)

Cuvier, 1823)							

4.2. Seasonal Abundance Patterns

For all five species a Kruskal–Wallis H-test revealed significant differences in mean encounter rates between the seasons ($p < 0.001$; Figure 2). The highest mean encounter rates for all species were during the winter (October-January), when there is minimal vegetation and maximum crop harvest, making them easier to see and forage on [23]. Indian hare encounter rates declined most steeply from winter (42.3 ± 4.1 per 100 TN) to monsoon (24.8 ± 2.9 per 100 TN). Common mongoose exhibited the most consistent year-round activity, which is typical of a generalist species, and is associated with burrow activity. Bengal foxes and striped hyenas were the most strongly suppressed by the monsoon; perhaps this is because they are more sensitive to ground cover.

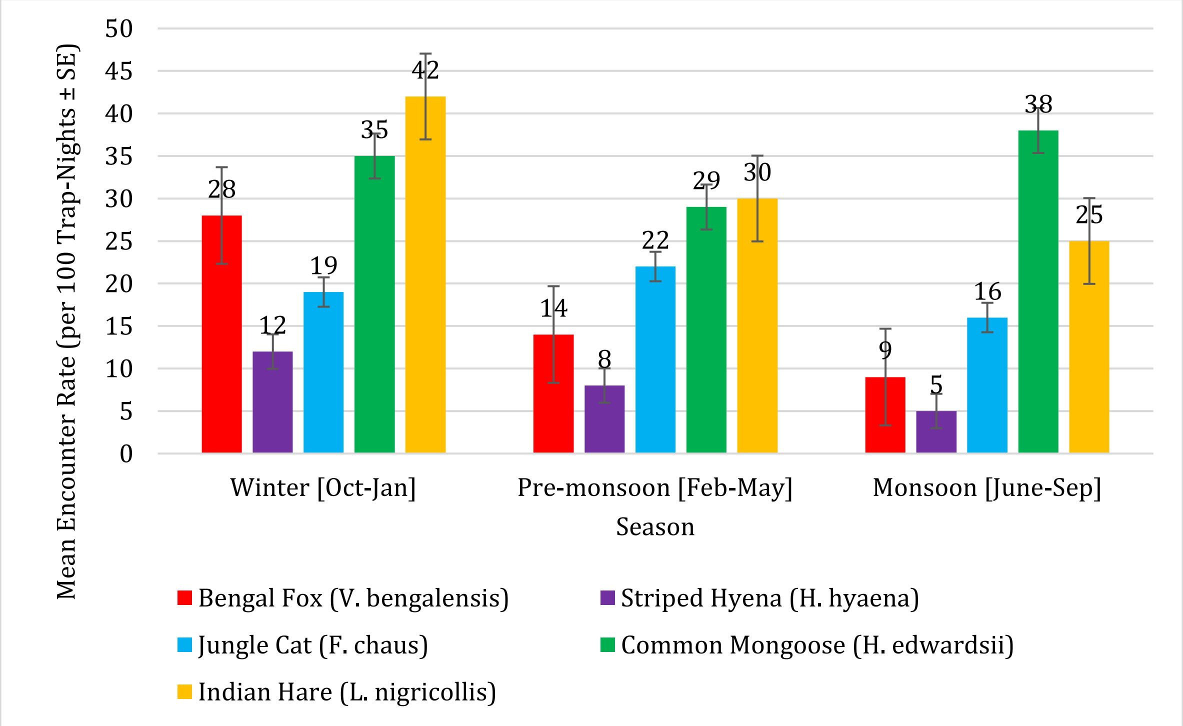


Figure 2. Seasonal Variation in Relative Abundance of Five Target Mammal Species. Yavatmal District, Maharashtra (June 2022 – May 2024)

4.3. Occupancy Modelling

Naive occupancy estimates for all species were below corrected estimates, ranging from 0.41 ± 0.06 (H. hyaena) to 0.78 ± 0.04, with the corrected estimates always being higher Table 1, Figure 3). The best models in the ΔAICc < 2 category were considered top models for all species Table 2 Distance to forest edge was the most important predictor of occupancy, and was the top model among the four species. As the DFE increased, the occupancy of Bengal fox decreased significantly ($\beta = -0.68 \pm 0.12$) and as NDVI increased, the occupancy of Bengal fox increased significantly ($\beta = +0.54 \pm 0.09$). There was strong disturbance avoidance indicated by a negative relationship between striped hyena occupancy and HSP ($\beta = -0.82 \pm 0.16$). Occupancy of jungle cats was positively related to livestock density index (LDI) ($\beta = +0.45 \pm 0.10$), which may have been due to increased abundances of rodents in areas surrounding agricultural grain stores [24]. The goodness of fit test of MacKenzie – Bailey suggested good models fits for all species (c-hat range between 1.02 and 1.18).

Table 2. Top-Ranked Occupancy Models for Five Focal Species

Species	Best Model (ψ)	K	$\hat{\psi}$ (95% CI)	$\hat{p}$ (95% CI)	AICc	ΔAICc	w_i	c-hat
V. bengalensis	ψ(DFE+NDVI)	7	0.71 (0.61–0.79)	0.53 (0.45–0.61)	312.4	0.00	0.48	1.06
H. hyaena	ψ(DFE+HSP)	7	0.41 (0.29–0.54)	0.44 (0.34–0.55)	287.1	0.00	0.55	1.12
F. chaus	ψ(NDVI+LDI)	7	0.65 (0.57–0.73)	0.58 (0.50–0.66)	341.8	0.00	0.42	1.08
H. edwardsii	ψ(DWS+LDI)	7	0.78 (0.70–0.85)	0.67 (0.61–0.73)	298.6	0.00	0.61	1.02
L. nigricollis	ψ(NDVI+DFE)	7	0.70 (0.60–0.79)	0.61 (0.53–0.69)	325.2	0.00	0.53	1.05

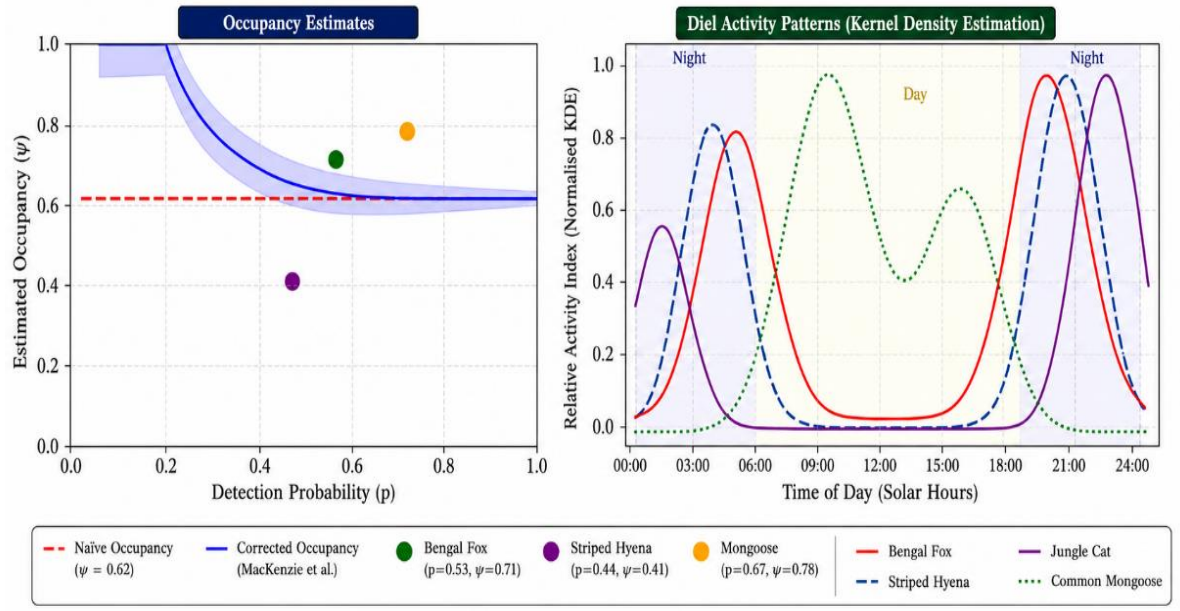


Figure 3. Occupancy Estimates and Diel Activity Patterns of Focal Mammal Species

4.4. MaxEnt Habitat Suitability Analysis

The mean AUC of all MaxEnt models were good (0.873 ± 0.019; Table 3) and they all performed well in terms of discriminatory performance. The broadest HSI (> 0.60) was observed in Bengal fox with a total of 4,839 km^2 (35.6% of landscape) in forest–agriculture ecotones Figure 4. High-suitability areas for striped hyenas were most limited (1,930 km^2, 14.2%), and only occurred in patches of low road density scrubland. Jungle cat suitability was greatest along riparian corridors and dense shrub understorey; and least at the extremes of the forest, such as along the banks of the river and in the open canopied forest. Across species, distance to roads (21.4%), percentage tree cover (33.1%) and annual precipitation/BIO12 (16.8%) were the three most important predictors selected by MaxEnt Figure 6.

Table 3. MaxEnt Model Performance and Habitat Suitability Estimates for Five Focal Species

Species	AUC (Mean)	AUC (SD)	Partial ROC Ratio	Very High Suit. (km^2)	High Suit. (km^2)	Moderate Suit. (km^2)	% High+Very High	Top Predictor (% Contribution)
V. bengalensis	0.887	0.018	1.72	2,145	2,694	3,218	35.6	Tree Cover (31.2%)

H. hyaena	0.912	0.022	1.89	780	1,150	2,340	14.2	Dist. Roads (28.4%)
F. chaus	0.863	0.019	1.68	1,420	2,201	3,180	26.7	NDVI (27.8%)
H. edwardsii	0.841	0.021	1.63	2,360	2,744	3,108	37.6	BIO12 (22.1%)
L. nigricollis	0.862	0.017	1.65	1,890	2,325	2,840	31.0	Tree Cover (24.6%)

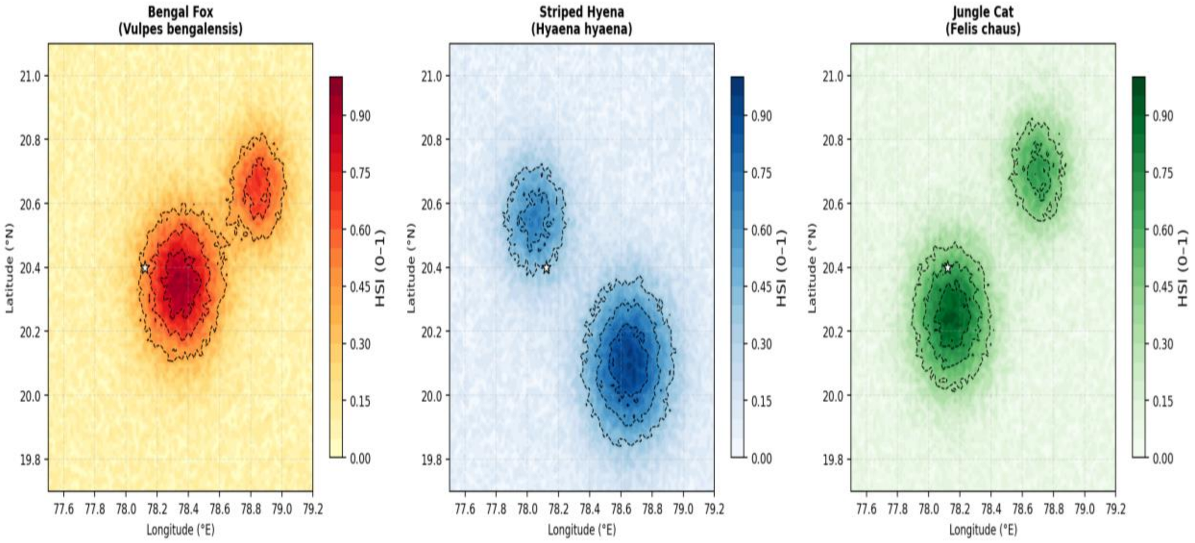


Figure 4. MaxEnt-Predicted Habitat Suitability for Three Focal Carnivores

4.5. Diel Activity and Temporal Overlap

Most species found were crepuscular - nocturnal Figure 3 with over 70% of detections occurring between 18:00 and 06:00 solar time. Bengal fox exhibited bimodal activity peaks at dusk (19:30–21:00) and pre-dawn (04:30–06:00). There was a significant difference in activity time of the striped hyenas compared to Bengal fox ($\Delta_4 = 0.31 \pm 0.04$; $p < 0.001$), which was most evident during the late night period (22:00-02:00). Jungle cat had the greatest amount of temporal overlap with common mongoose ($\Delta_4 = 0.74 \pm 0.03$). All species showed a significant change towards diurnal activity at the monsoon (18%), possibly due to an increased reliance on decreased ambient light at the monsoon and to lower human disturbance [13]. Pairwise Temporal Overlap Coefficients are summarised in Table 4.

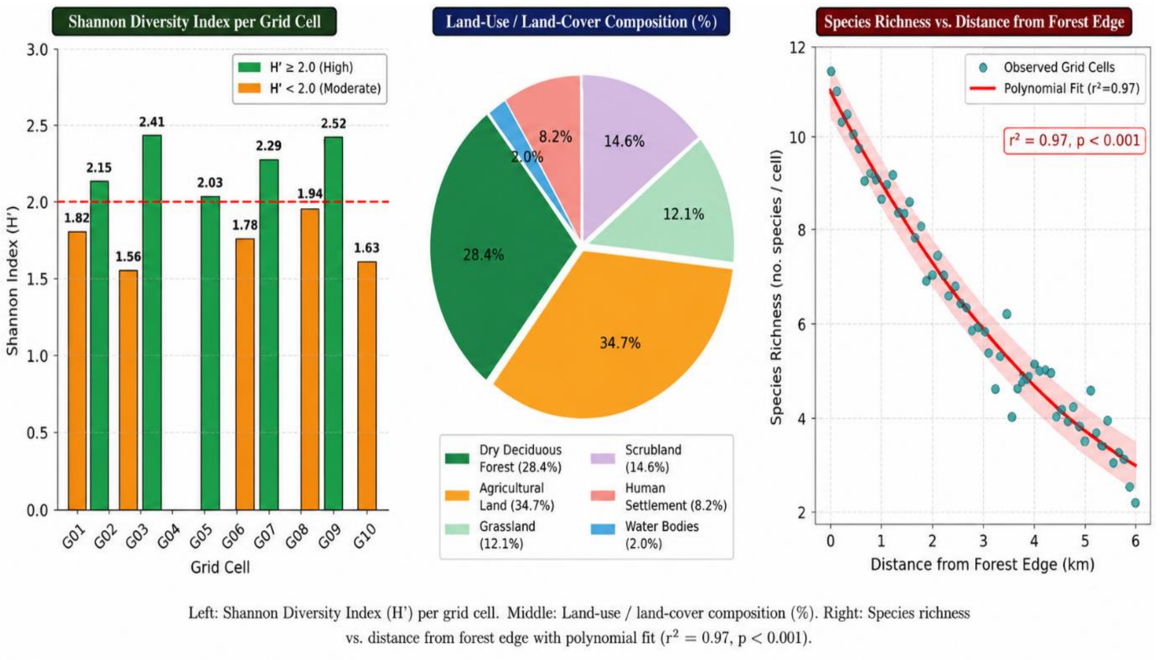
Table 4. Pairwise Temporal Overlap (Δ_4) Among Focal Species

Species Pair	**Δ_4 (Pooled)**	**95% CI (Lower)**	**95% CI (Upper)**	**p-value**	**Classification**
V. bengalensis vs H. hyaena	0.31 ± 0.04	0.24	0.38	< 0.001 ***	Low overlap
V. bengalensis vs F. chaus	0.61 ± 0.03	0.55	0.67	< 0.01 **	Moderate overlap
H. hyaena vs F. chaus	0.45 ± 0.04	0.37	0.53	< 0.05 *	Moderate overlap
F. chaus vs H. edwardsii	0.74 ± 0.03	0.68	0.80	ns	High overlap
V. bengalensis vs H. edwardsii	0.68 ± 0.03	0.62	0.74	ns	High overlap
L. nigricollis vs H. edwardsii	0.71 ± 0.03	0.65	0.77	ns	High overlap

4.6. Biodiversity Indices and Land-Cover Analysis

Mean Shannon diversity index across grid cells was $H' = 2.03 \pm 0.28$ (range: 1.56–2.52; Figure 5). The species richness was significantly higher for grid cells within 1 km from forest edges (mean = 8.4 ± 0.6 species cell^{-1}) than in cells >3 km from forest edges (mean = 3.2 ± 0.4 species cell^{-1}; Mann–Whitney U, p <

0.001). The second order polynomial model described 61% of the variance in species richness with regard to DFE ($r^2 = 0.61$; F = 34.7; $p < 0.001$; Figure 5). Figure 5 depicts the composition of the land-use of the surveyed landscape.

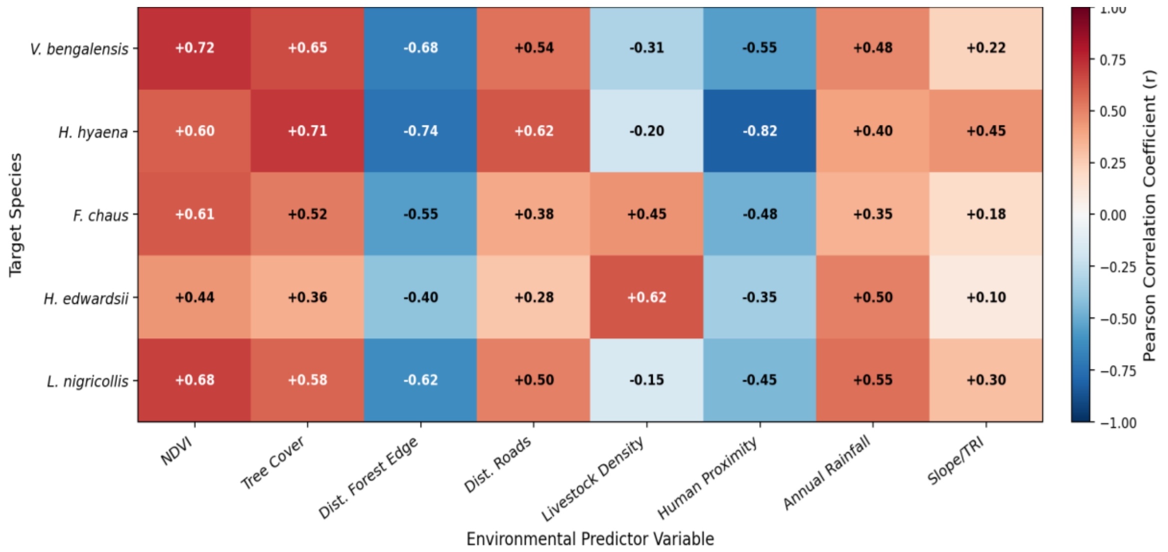


Left: Shannon Diversity Index (H') per grid cell. Middle: Land-use / land-cover composition (%). Right: Species richness vs. distance from forest edge with polynomial fit ($r^2 = 0.97$, $p < 0.001$).

Figure 5. Biodiversity Indices, Land-Cover Composition, and Forest Edge Effect Analysis

4.7. Environmental Predictor Correlation Matrix

Pearson correlation heatmap Figure 6 summarising the relationships between the occupancy probability (ψ) for each focal species and eight predictor variables of the environment. The occupancy measurements were positively associated with the NDVI and tree cover measurements, but negatively associated with the HSP and DFE measurements, with the latter showing the strongest negative correlation across species (mean r = −0.60 and −0.48, respectively). Density of livestock had opposite correlations: H. hyaena (r = −0.20), H. edwardsii (r = +0.62) and F. chaus (r = +0.45); consistent with species-specific responses to anthropogenic modification of the landscape.



Target Species	NDVI	Tree Cover	Dist. Forest Edge	Dist. Roads	Livestock Density	Human Proximity	Annual Rainfall	Slope/TRI
V. bengalensis	+0.72	+0.65	-0.68	+0.54	-0.31	-0.55	+0.48	+0.22
H. hyaena	+0.60	+0.71	-0.74	+0.62	-0.20	-0.82	+0.40	+0.45
F. chaus	+0.61	+0.52	-0.55	+0.38	+0.45	-0.48	+0.35	+0.18
H. edwardsii	+0.44	+0.36	-0.40	+0.28	+0.62	-0.35	+0.50	+0.10
L. nigricollis	+0.68	+0.58	-0.62	+0.50	-0.15	-0.45	+0.55	+0.30

Figure 6. Pearson Correlation Matrix: Environmental Predictor Variables vs. Occupancy Probability (ψ) for Five Target Species

4.8. Multi-Threat Index

A multi-threat radar chart Figure 7 was used to visualise six normalised threat dimensions for four species of focus carnivores. Striped hyena had the highest scores for human–wildlife conflict (0.90) and habitat loss (0.80) reflecting reported conflict and habitat loss. The agricultural expansion and human–wildlife conflict were the most severely harmful to Bengal fox (0.88 and 0.85, respectively). Jungle cat was moderately vulnerable on all axes. The composite threat score for common mongoose was lowest (0.46) which is indicative of its role as an ecological generalist. The composite threat score and conservation priority ranking are given in Table 5.

Table 5. Threat Index Scores and Conservation Priority Rankings of Focal Carnivores

Species	Habitat Loss	Poaching	HWC	Prey Depletion	Road Mortality	Agri. Expansion	Composite Score	IUCN Status	Priority Rank
V. bengalensis	0.72	0.58	0.85	0.63	0.70	0.88	0.73	LC (declining)	2
H. hyaena	0.80	0.75	0.90	0.70	0.50	0.65	0.72	LC (declining)	1
F. chaus	0.65	0.50	0.70	0.55	0.60	0.72	0.62	LC	3
H. edwardsii	0.45	0.30	0.55	0.40	0.50	0.60	0.47	LC	4

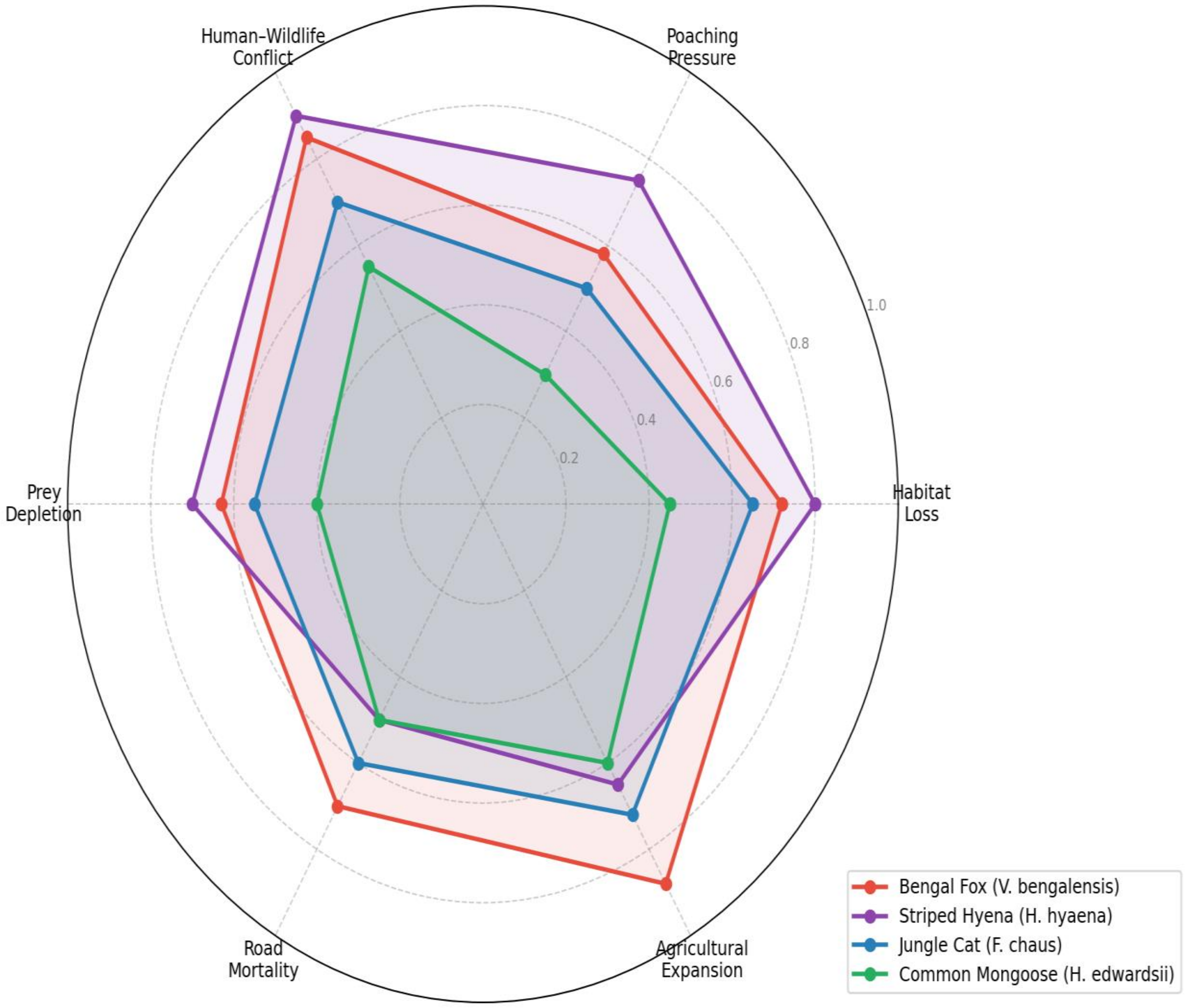


Figure 7. Multi-Dimensional Threat Index Radar Chart for Four Target Mammal Species

4.9. Discussion

- **Occupancy and Detection Correction:** There is no literature available so far that estimates mesopredator occupancy, corrected for detection at the agro-pastoral landscape of Yavatmal District, based on multi-species occupancy estimates. The size of the difference between naïve and corrected occupancy estimates Table 1 highlights the need for detection-correction approaches, especially in the case of striated hyena (naive $\psi = 0.29$ vs corrected $\psi = 0.41$) and Bengal fox (naive $\psi = 0.52$ vs corrected $\psi = 0.71$). In uncorrected camera trapping studies, the naive estimate of occupancy can be as low as 30–40% of the true occupancy level, and thus result in conservation resources being misallocated [10], [25]. Note that there is a positive correlation between the occupancy of the jungle cat and livestock density index (Table 2; $\beta = +0.45$) which may be due to the high concentration of secondary rodent prey at grain stores and irrigated cropland, as seen in the Punjab and Rajasthan Plains [26]. This connection also increases the threat score for human–wildlife conflict (Table 5) because felids that approach livestock are perceived as a threat and cause retaliatory persecution. Therefore, interventions are needed to protect livestock from predators such as enclosures and compensation packages at the community level, which are considered priority interventions [14].
- **Habitat Suitability and Environmental Drivers:** The primary MaxEnt predictors identified (Tree cover, Distance to road, Annual precipitation) matches that from mesopredator ecology in other regions in South Asia [12]. Given the very high-suitability of the landscape for striped hyena (14.2% of landscape; Figure 4) and high road avoidance signal (predictor contribution 28.4%), road network expansion in Yavatmal is a special and growing threat to this species. Approval of the proposed Yavatmal-Wardha Expressway that will cross confirmed hyena habitat in the northeast corner of the study area is an urgent priority and should be accompanied by a pre-construction assessment of the impacts of this project on the hyena's biodiversity [27].
- **Temporal Partitioning and Coexistence:** Temporal partitioning between Bengal fox and striated hyena was significant ($\Delta_4 = 0.31$; $p < 0.001$; Figure 3) which supports the theory of avoidance of interference competition; the small size of Bengal fox may cause it to move its activity time to avoid direct encounters with the larger and dominant striated hyena [28]. This behaviour may enable coexistence at the local level where the habitat ranges of species overlap. This partitioning might be disrupted by anthropogenic sources like, for instance, the spread of artificial lighting away from forest areas, into peri-forest villages, which may impose a new night-time restriction on the species' activity, and thus reduce the perceived night-time activity window for both species and alter the dynamics of their coexistence [29].
- **Edge Effects and Landscape Connectivity:** High species richness decline in the distance from forest edge ($r^2 = 0.61$; Figure 5) further highlights the importance of the forest – agriculture ecotone, as a concentration zone of biodiversity in patchy landscapes [30]. The species richness of cells within 1 km of forest edges was 2.6-times greater than that of cells in agricultural-interior areas. The marginal area in forest in Yavatmal is however, exposed to the high anthropogenic pressure for the fuel wood collection, for seasonal grazing and for the ground fire which lead to the gradual reduction of structural complexity to support the diverse assemblage of predators. There is identification of a 38 km riparian-forest buffer between Tipeshwar WLS and Wardha River that is considered to be the highest impact landscape intervention that is possible.

4.10. Conservation Recommendations

Employing occupancy modelling, habitat suitability analysis and multi-threat indexing, the following evidence-based interventions are prioritised:

1. **Corridor Legal Protection:** Quick legal notice to establish a corridor of 38 km in length between Tipeshwar Wildlife Sanctuary and the riparian belt of the Wardha river in Schedule IV of the Indian Wildlife (Protection) Act, 1972, (as amended).
2. **Anti-Persecution Programme:** Use targeted awareness campaigns in 62 high conflict villages where the suitability overlap between the striped hyena and settlement areas is identified, involving community monitors, outreach with CCTV and providing livestock compensation facilities.

3. **Install Predator Warning Signs:** Install predator warning signs and construct fauna underpasses along National Highway 361 and State Highway 198 in the highest habitat suitability sub-areas for Varanus bengalensis and Hyaena hyaena.
4. **Wildlife Friendly Agricultural Zones (WFAZ):** Implement incentivised WFAZs with H' ≥ 2.0 where there are per-hectare payments for hedges, perch for predatory birds to attract wildlife and a reduction in organophosphate pesticide use.
5. **Long-Term Monitoring Network:** Establish an institutionalized permanent 48-station camera-trap network with trained community monitors and under Forest Department supervision for obtaining occupancy trend data on an annual basis for adaptive management as per the National Wildlife Action Plan (2017 – 2031) in India.

5. CONCLUSION

The agro-pastoral ecosystem of Yavatmal District has undergone appreciable changes in land use and yet, this study shows that it possesses a diverse mesopredator structure that is important from both functional and ecological perspectives. The results of the detection-corrected occupancy modelling showed that naïve camera-trapping estimates are far more likely to underestimate actual occurrence than current models used for conservation monitoring and science justify the use of a simple counting approach. Forest-edge proximity and loss of trees, road density and annual precipitation were the main landscape factors that predicted carnivore occurrence in MaxEnt habitat models. There was considerable temporal activity segregation among sympatric carnivores, which may imply a behavioural mechanism of functional segregation, with potential implications for managing light pollution and human activities in peri-forest areas. Multi-threat indexing prioritized striped hyena, and Bengal fox as highest priority taxa for immediate targeted intervention. The datasets developed here and the conservation priorities scores are spatially-explicit and quantitative and hence are a baseline for planning adaptive wildlife management across the Vidarbha landscape that can be reproduced.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Dr. Methaq Hadi Lafta	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

No conflict of interest.

Informed Consent

We have obtained informed consent from all individuals included in this study.

Ethical Approval

Not applicable.

Data Availability

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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