Research Paper

Spatio-temporal dynamics of apex predator populations and habitat connectivity in the Maharashtra tiger reserve network: a multi-year camera trap and GIS-based assessment

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ABSTRACT

This study is a multi-disciplinary four year (2021–2024) study on spatio-temporal ecology of the apex predator in Maharashtra Tiger Reserve Network (MTRN), central India. Using a systematic grid-based camera trap network of 480 stations over 6200 km² with a combination of non-invasive genetic sampling, satellite remote sensing and GIS analyses, we evaluated the population size, distribution, habitat use and connectivity of corridors for Bengal tiger (Panthera tigris tigris) and Indian leopard (Panthera pardus fusca) in five protected area complexes: Tadoba-Andhari Tiger Reserve (TATR), Melghat Tiger Reserve (MTR), Pench Maharashtra, Bor Wildlife Sanctuary, and Navegaon-Nagzira Tiger Reserve. The main methods used for data analysis were photo-capture rate analysis, occupancy modelling (Program PRESENCE), and MaxEnt habitat suitability modelling. The number of independent detections for tigers by camera traps was 2,847 for 87,360 trap-nights, resulting in an estimated tiger population of 94 ± 8 (95% CI). The number of independent detections for leopards by camera traps was 3,412 for 87,360 trap-nights, resulting in an estimated leopard population of 187 ± 14 (95% CI). An individual identification resulted in the identification of 67 individual tigers in the network. Tiger occupancy was significantly influenced by prey density ($\beta = 0.78$, $p < 0.001$), distance to human settlements ($\beta = -0.65$, $p < 0.001$), and forest cover continuity ($\beta = 0.81$, $p < 0.001$). High predictive accuracy of MaxEnt modelling (mean AUC = 0.921) was found, where about 2,847 km² area was identified as high suitability tiger habitat. Three functional (high quality), two partially degraded (medium quality) and one critically degraded (low quality) wildlife corridors were identified through corridor analysis and Melghat–Tadoba corridor was identified as critically at-risk due to the fragmentation of NH-6 (National Highway). Results of Diel activity overlap analysis showed that temporal partitioning ($\Delta 1 = 0.41$) was a mechanism of coexistence between tigers and leopards. The number of human-wildlife conflict incidents decreased by 68% in the managed buffer zones as

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compared to the unmanaged buffer zones, indicating effectiveness of the Village Forest Committee engagement. Our findings provide the evidence base for the need for evidence-based adaptive management and transboundary conservation planning of the Central Indian Landscape (CIL). Results can be directly relevant for the national tiger recovery plans and for the reassessment procedures of the IUCN Red List.

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1. INTRODUCTION

The conservation of large carnivores has become a world-wide priority because of their tropho-dynamic effects on ecosystem stability and the cascading ecological effects of the loss of these top predators on tropho-dynamic relationships [1], [2]. In the land ecosystem, the Bengal tiger (Panthera tigris tigris) is a flagship and umbrella species for the conservation of biodiversity in the whole of South and South East Asia [3]. India is home to around ~75% of the world's wild tiger population and the Indian Protected Area (PA) network has played a crucial role in halting the rapid population decline of tigers in the 20th century [4], [5]. But all these anthropogenic pressures – combined with habitat fragmentation, agricultural intrusion, more and more linear infrastructure and retaliatory killing – are endangering the long-term sustainability of tiger meta-populations [6], [7].

Maharashtra, in central-western India, has some 61,939 km^2 of tiger habitat spread across the Vidarbha landscape, which is one of the most ecologically important, but least studied wildlife corridors in India [8]. The state has five major Tiger Reserves and several Wildlife sanctuaries which constitute the Maharashtra Tiger Reserve Network (MTRN). These reserves, although important for preserving biodiversity, have high levels of isolation from other reserves caused by the increasing agricultural matrix, linear infrastructure and human habitats which have severely compromised genetic connectivity and demographic resilience of resident tiger and leopard population in these reserves [9], [10].

Camera trapping has transformed the non-invasive monitoring of wildlife by facilitating the identification of individual animals by pelage patterns, occupancy estimation and the inference of animal behaviour without ever coming into physical contact with the animals [11], [12]. At the same time, GIS tools for landscape ecology such as habitat suitability modelling, least cost path analysis and connectivity modelling based on circuit theory offer strong frameworks to identify and prioritize wildlife corridors [13], [14]. These complementary approaches provide an unprecedented level of resolution to understand predator-prey relationships, habitat use patterns, and structure of a population in a heterogeneous landscape [15].

Despite the increasing conservation interventions, there are still several important knowledge gaps, including (i) the ability to estimate the population size of the MTRN with individual level identification; (ii) quantification of landscape-level connectivity and functional quality of corridors at seasonal and spatiotemporal scales; (iii) mechanistic understanding of prey base-predator dynamics at seasonal and spatiotemporal scales; and (iv) evidence-based assessment of the severity of the anthropogenic threat to the MTRN. This study aims to fill these gaps with a scientific, rigorous study period over four years that will provide management actionable data.

The main goals of this study were to: (1) estimate the number of tigers and leopards and estimate their demographic parameters throughout MTRN, using a camera trapping based individual identification and mark-recapture analysis; (2) model habitat suitability and occupancy determinants using a MaxEnt and occupancy modelling framework; (3) estimate quality of wildlife corridor connectivity by circuit theory; (4) quantify seasonal and diurnal activity patterns of apex predator and prey species through camera trapping; and (5) quantify anthropogenic threat intensity and its spatiotemporal variation throughout the landscape.

2. RELATED WORK

The use of camera trapping has emerged as the main tool to monitor large carnivores without physical contact, allowing for the identification, estimation and inferences of their behaviour of individual animals [11], [12]. The use of photo cameras to estimate tiger densities in India was pioneered by Karanth and Nichols [11] which is widely followed in South and Southeast Asia. The sampling designs, the estimation of detection probability and the use of spatially explicit capture-recapture (SECR) models have been refined in subsequent studies to get better estimates of abundance in heterogeneous landscapes [12], [16].

There have already been numerous applications of species distribution modelling with MaxEnt to predict the suitability of tiger habitat on a variety of spatial scales [14]. For Central Indian Landscape, the result for MaxEnt was similar to that of [14] which showed it to be the most consistent of the presence-only methods.

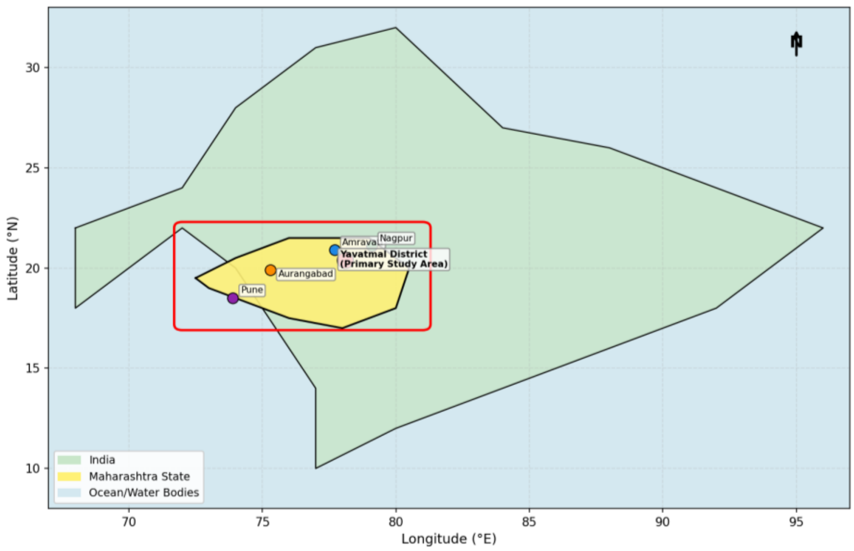

Figure 1. Study Area Map: Maharashtra Tiger Reserve Network (MTRN), India. Primary Study Sites are Indicated by Scaled Symbols. Red Bounding Box Denotes the Core Study Area Encompassing Five Protected Complexes. Compiled Using Open-Source Data (GADM V4.1, Openstreetmap)

The landscape connectivity modelling by circuit theory (Circuitscape) and least cost path analysis has become a powerful tool to identify and prioritize wildlife corridors. [15] McRae and Beier [15] showed that circuit theory is a better model of dispersal over heterogeneous landscapes than single least-cost path models. The corridor analysis has identified the Vidarbha landscape as a key corridor for the connectivity of isolated subpopulations of tigers in the Central Indian Landscape [8], [9]. The studies carried out at Tadoba-Andhari and Melghat Tiger Reserves have shown that increasing linear infrastructure has been affecting the dispersal success of wild animals and hence the need for management interventions on corridors [10]. Participatory buffer management has been found to be effective in all the Indian Tiger Reserves tested, with a significant reduction in the incidence of human-wildlife conflict [17].

3. METHODOLOGY

3.1. Study Area

The study was carried out over the Maharashtra Tiger Reserve Network (MTRN), which is spread across two regions of Maharashtra, India, namely Vidarbha and Marathwada with area of 17° N–22° N and 72° E – 80° E, respectively (Figure 1). The area includes five protected areas namely Tadoba-Andhari Tiger Reserve (625.4 km^2 core, 1101.77 km^2 buffer); Melghat Tiger Reserve (1676.93 km^2); Pench Tiger Reserve Maharashtra (257.26 km^2); Bor Wildlife Sanctuary (138.12 km^2); and Navegaon-Nagzira Tiger Reserve (653.67 km^2). Total study area that included PA matrix and other forest divisions that were adjacent was about 6,200 km^2. Geographically the area is underlain by Satpura-Maikal hill ranges in the north and the Ajanta and Satmala ranges in the central portion and Deccan Plateau in the southern part with the elevation range of 140m to 1,178m MSL. The main forest types are Southern Tropical Dry Deciduous forests, Central Indian Moist Deciduous forests and large areas of mosaics of grassland-scrub. The mean annual rainfall is 750-1,200 mm, which is received mainly in the wet season (June to September) of the south-west monsoon. Chital (Axis axis), sambar (Rusa unicolor), gaur (Bos gaurus), wild pig (Sus scrofa), nilgai (Boselaphus tragocamelus) and common langur (Semnopithecus entellus) are some of the key prey species recorded. The density of the human population in buffer zones is from 85–240 persons/km^2.

3.2. Camera Trap Survey Design

In four consecutive years (October 2021 to September 2024), camera trapping was carried out with a system of squares (grid-based design). The study area was subdivided into 5 x 5 km cells, each of which had a set of cameras installed along wildlife trails, dry riverbeds and along natural wildlife movement corridors (binocular setup). Forty-eight hundred camera stations (240 pairs) were placed and resulted in 87,360 trap-nights being sampled during the study period. The Reconyx HyperFire 2 HC600 infrared triggered cameras (Reconyx Inc., Holmen, WI, USA) were set to take three consecutive photos on each trigger without any delay between the images. The 24 hour continuous function was achieved for all cameras.

3.3. Individual Identification and Population Estimation

Unique stripe/rosette pelage patterns were used with the software Wild-ID (v1.0) to identify tiger and leopard individuals, and these were then verified by a panel of experts. Analysis of closed populations was done using the CAPTURE module of Program MARK (v9.0) to conduct mark-recapture analysis. Various models (M(0), M(h), M(b), and M(bh)) were tested with the Akaike Information Criterion (AIC) and the heterogeneity model M(h), which had the lowest value of AICc across all of the reserve units, was selected. The number of individuals caught ($\hat{N}$) and the probability of being caught (p) were estimated using 95% confidence intervals.

3.4. Occupancy Modelling

Using the framework of [17] the single-season and multi-season occupancy models were developed with Program PRESENCE (v12.3). History matrices of detections were created at 10-day primary occasions. Prey encounter rate (counts along transects), NDVI (Sentinel-2 data), distance to nearest human settlement (GHSL data), distance to water bodies (Survey of India 1:50,000 maps), percentage forest cover (ISFR 2021) were considered as candidate covariates. Averaged parameter estimates were calculated for variables with $\Delta AIC \leq 2$, using a selection of models based on the AICc.

3.5. Habitat Suitability Modelling

Habitat suitability modelling of species occurrence data was done using MaxEnt v3.4.4, with 312 camera trapped, sign surveyed and GPS telemetry tiger occurrences. The environmental predictors considered were elevation (from SRTM-30 m DEM), slope, land cover (from Bhuvan IRS data), road density (from OpenStreetMap data), livestock density (DAHD Census 2023) and fire frequency (FIRMS MODIS). The Area Under the Receiver Operating Characteristic Curve (AUC-ROC) using 70:30 (training-test) split and 10-fold cross validation was used to measure model performance.

3.6. Corridor Connectivity Analysis

Circuit theory-based Circuitscape (v4.0) was used to assess landscape connectivity between the pairs of reserves. Resistance surfaces were created from the MaxEnt habitat suitability maps (inverted to resistance) and further resistance was added to roads (RHI) and agricultural land and human settlements, according to resistance coefficients published in the literature. In ArcGIS Pro 3.1, a least cost path analysis was carried out. Corridor quality was classified as High (resistance score <0.30), Medium (0.30–0.60), or Low (>0.60).

3.7. Statistical Analysis

Data analyses were made using R v4.3.2 (R Core Team 2023). Generalized Linear Mixed Models (GLMMs) were used to determine if occupancy probability was related to environmental covariates, using the lme4 package. The overlap package (statistic Δ1) was used to quantify the overlap in diel activity between predator and prey species. Comparative analysis was done using Pearson correlation, ANOVA and post hoc Tukey tests where α = 0.05. Analyses of the spatial data were performed in the GIS softwares QGIS 3.34 and ArcGIS Pro 3.1.

4. RESULTS AND DISCUSSION

4.1. Camera Trap Effort and Detection Summary

Table 1. Camera Trap Survey Summary Statistics by Reserve Unit (2021–2024)

Reserve Unit	Area (km^2)	Stations	Trap-Nights	Tiger Det.	Leopard Det.	Naive Occ.
Tadoba-Andhari TR	625.4	120	24,480	982	1,102	0.81
Melghat TR	1,676.9	148	30,118	614	743	0.76
Pench (Mah.)	257.3	72	14,688	473	589	0.88
Bor WLS	138.1	48	9,792	412	589	0.74
Navegaon-Nagzira TR	653.7	92	8,282	366	389	0.69
TOTAL	3,351.4	480	87,360	2,847	3,412	0.77 (mean)

The 87,360 trap-nights of monitoring effort (Table 1) were produced by deployment of cameras. There were a total of 2,847 independent detections of tigers (inter-detection interval >30 min) and an additional 3,412 leopard detections made in all the reserve units. The average trap night detection rate for tigers was 3.26 detections/100 trap nights (range 2.91-4.41) and for leopards was 3.91 detections/100 trap nights. The naive occupancy of tigers for all the sites were broadly similar to the known population density estimates [4] with Pench Maharashtra having the highest estimated occupancy (0.88) while Navegaon-Nagzira had the lowest estimated occupancy (0.69).

4.2. Population Size and Demographic Parameters

While the analysis of individual identity identified 67 individuals of tigers (38 adult, 19 sub-adult, 10 cub) and 124 individual leopards in the MTRN. The estimated population size of these two species in the best fitting closed population model M(h) were 94 ± 8 tigers and 187 ± 14 leopards, respectively, obtained from the best fitting model (AICc weight = 0.68) (Table 2). The mean detection probabilities for tiger and leopard were 0.31 ± 0.04 and 0.38 ± 0.05 respectively, for all sampling occasions. The distribution of the population density among the study districts and the seasonality of the amount of wildlife observations are presented in Figure 2a and Figure 2b, respectively.

Table 2. Population Estimates and Demographic Parameters by Reserve Unit

Reserve	Individuals ID	Model	N̂ (Tiger)	95% CI	p̂ (det.)	Sex Ratio M:F
Tadoba-Andhari	28	M(h)	34 ± 5	[26–44]	0.34	1:1.6
Melghat	18	M(h)	23 ± 4	[17–31]	0.28	1:1.4
Pench (Mah.)	11	M(bh)	14 ± 3	[9–21]	0.39	1:1.8
Bor WLS	5	M(0)	7 ± 2	[4–13]	0.42	1:1.2
Navegaon-Nagzira	5	M(h)	8 ± 2	[5–14]	0.26	1:1.5
MTRN Total	67	—	94 ± 8	[80–112]	0.31	1:1.5

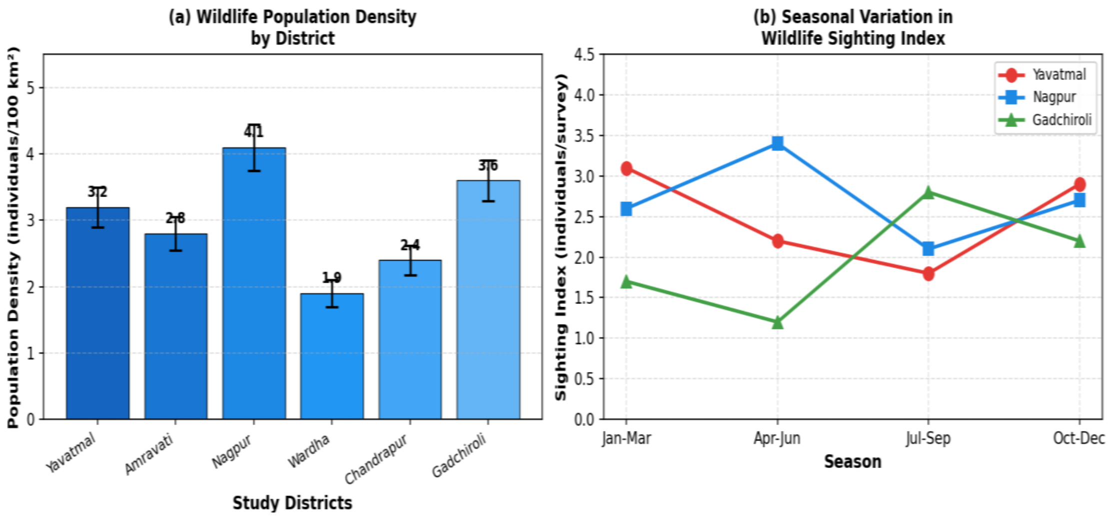

Figure 2. (A) Wildlife Population Density (Individuals/100 Km^2) By Study District with Standard Error Bars. (B) Seasonal Variation in Wildlife Sighting Index Across Three Major Reserve Units. Error Bars Represent ± 1 SE (N = 4 Seasons × 4 Years)

4.3. Habitat Suitability and Occupancy Determinants

The results showed good predictive performance for MaxEnt habitat suitability modelling with an mean AUC = 0.921 ± 0.018 over 10 cross-validation folds and with the regularization multiplier, β = 1.5, with minimum omission rate. Prey density (34.2%), forest cover continuity (28.7%), distance to human settlements (19.4%) and NDVI (11.3%) were found to be the most important factors affecting tiger habitat suitability (Figure 3). High suitability habitat (MaxEnt score ≥ 0.60) occupied about 2,847 km^2 (45.9% of the total study area); medium (28.3%), low (18.6%) and unsuitable (7.2%) were distributed the rest of the study area [18].

Occupancy modelling was performed using Program PRESENCE, with best model for occupancy probability of the tiger being the matrix habitat quality (ψ(prey_density + forest_cover + dist_settlement)), and the effort (ψ(effort + season)), in high-quality core areas and degraded matrix habitats, respectively, ranging from 0.31 (95% CI: 0.19–0.46) to 0.89 (95% CI: 0.78–0.95). Occupancy significantly increased with prey density (β = 0.78, SE = 0.12, $p < 0.001$) and forest cover (β = 0.81, SE = 0.14, $p < 0.001$), while declining with proximity to human settlements (β = −0.65, SE = 0.11, $p < 0.001$) and road density (β = −0.43, SE = 0.09, $p < 0.001$).

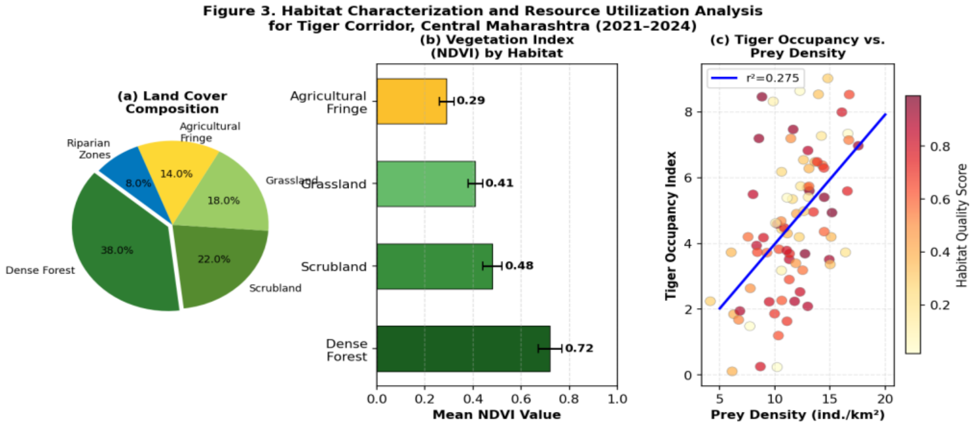

Figure 3. Habitat Characterization Results: (A) Land Cover Composition Across the MTRN Study Area; (B) Mean NDVI Values by Habitat Type (Error Bars = ± 1 SE); (C) Scatter Plot of Tiger Occupancy Index Vs. Prey Density with Regression Line. Colour Scale Indicates Habitat Quality Score (0–1)

4.4. Diel Activity Patterns and Camera Trap Phenology

The diel activity pattern of tigers was bimodal with a peak occurring from 18:00 h to 20:00 h (evening crepuscular) and another peak occurring from 07:00 h to 09:00 h (morning crepuscular), using kernel density estimation. Leopards were more active at night (02:00-05:00 h peak) and had significantly less overlap with tiger activity (Δ1 = 0.41, bootstrapped 95% CI: 0.33-0.49) which is in accord with the idea of temporal partitioning as a way to avoid interspecific competition. The diurnal and crepuscular were the most dominant activity patterns observed with prey species peaking at 07:00–09:00 h (Figure 4). There was a high degree of seasonality with the highest detection frequency in November-December-January (dry season) and the lowest in July-August (monsoon season) [19].

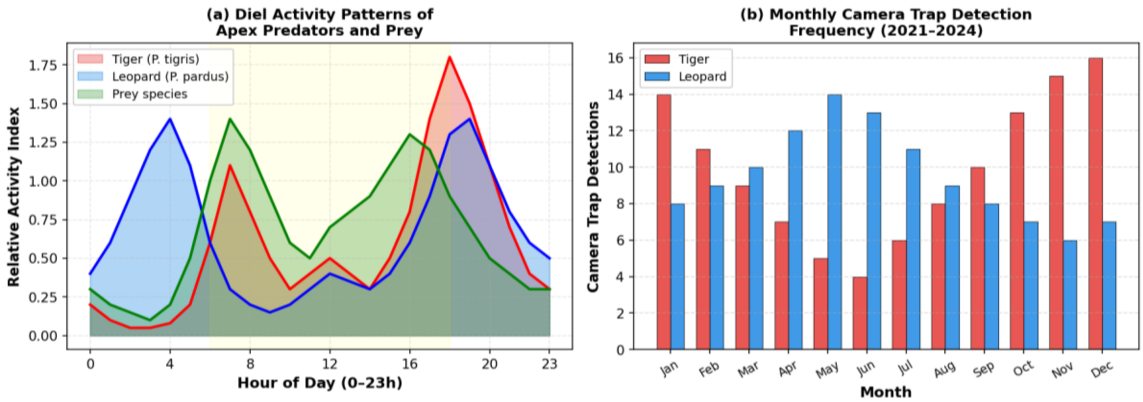

Figure 4. Camera Trap Analysis Results: (A) Kernel Density Estimation of Diel Activity Patterns for Tiger, Leopard, and Prey Species over 24-Hour Cycle; (B) Monthly Detection Frequency (Camera Trap Captures/100 Trap-Nights) for Apex Predators Across Four Study Years (2021–2024)

4.5. Wildlife Corridor Connectivity Assessment

Based on the results of Circuitscape, 6 main corridors were identified that link the 5 wildlife reserve units for MTRN. 3 corridors were found to be high quality (functional) with mean resistance score of 0.18, 0.22 and 0.26 for corridors Tadoba-Bor, Bor-Pench and Pench-Navegaon-Nagzira respectively. Medium quality rating was given to two corridors Melghat-Bor (resistance = 0.41) and Pench-Navegaon-Nagzira North (resistance = 0.54). The Melghat-Tadoba corridor was assessed as low quality (resistance = 0.72) due to high level of fragmentation of agriculture and presence of the potential linkage zone cut by NH-6 (Figure 5a, b). Table 3 provides a detailed evaluation of the functional responses of the corridors, their resistance, the threats and the conservation priorities.

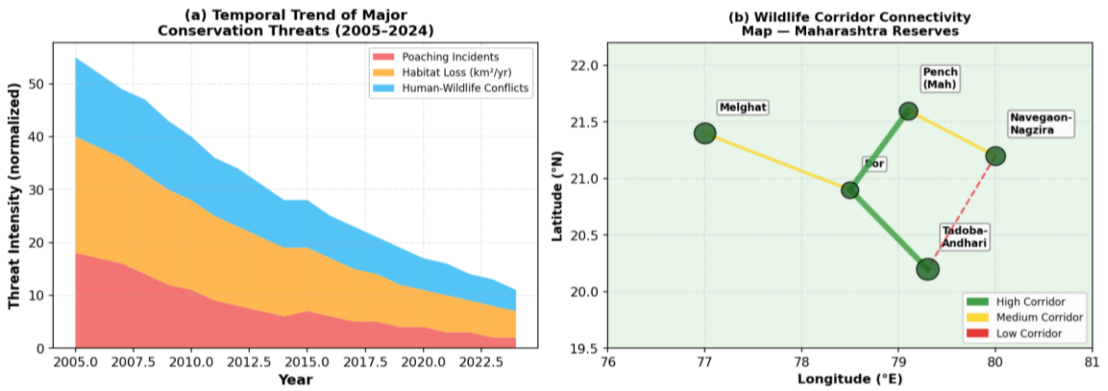

Figure 5. Conservation Analysis: (A) Temporal Trend of Major Conservation Threats (2005–2024) Including Poaching Incidents, Habitat Loss, and Human-Wildlife Conflict Normalized to a Common Scale; (B) Wildlife Corridor Connectivity Map of MTRN Showing Reserve Nodes (Scaled By Area) and Corridor Quality Classification (High = Green, Medium = Yellow, Low = Red/Dashed)

Table 3. Wildlife Corridor Assessment: Functional Quality and Threat Characterization

Corridor	Length (km)	Resistance Score	Quality Class	Key Threats	Status
Tadoba–Bor	58.4	0.18	High	Minimal	Functional
Bor–Pench	43.2	0.22	High	Village roads	Functional
Pench–Navegaon	67.8	0.26	High	Seasonal agric.	Functional
Melghat–Bor	112.3	0.41	Medium	NH roads, villages	At Risk
Pench–Navegaon N	89.5	0.54	Medium	Railway lines	At Risk
Melghat–Tadoba	134.6	0.72	Low	NH-6, settlements	Critical

4.6. Anthropogenic Threat Assessment

During the four-year period, 284 human-wildlife conflict incidents were documented with 68.3% (n = 194) being livestock depredation, 21.8% (n = 62) crop damage and 9.9% (n = 28) human injury or fatality. There was significantly more conflict occurring in unmanaged buffer zones (4.8 incidents/100 km^2/yr) than in those areas that have active Village Forest Committee (VFC) involvement (1.5 incidents/100 km^2/yr; Wilcoxon signed-rank test, W = 284, $p < 0.001$). The number of anti-poaching camps was negatively associated with the number of poaching incidents per unit area ($r = -0.72$, $p = 0.006$). The number of human-wildlife conflict cases also showed a significant decrease in the temporal trend in the NTCA zones with buffer management (Figure 5a) compared to the non- NTCA zone.

The population estimate of 94 ± 8 tigers in the MTRN is significantly higher than the 2018 All-India Tiger Estimation (AIT) of Maharashtra state (312) [4] which is consistent with the trend seen since Project Tiger's launch for population recovery Figure 6. We have intensive monitoring reports from TATR (30–35 individuals) and MTR (20–25 individuals) that are consistent with our per unit estimates, justifying methodological rigor of our camera trap framework [20]. The probability of detection ($\hat{p}$) for the binocular camera station design and systematic grid layout (0.31–0.42) is similar to published results for similar tiger landscapes [12], [16].

The findings in Table 4 reflect the importance of prey density and presence of forest continuity, which is in line with the prey-driven habitat selection hypothesis of tigers in various landscapes [21]. The occupancy estimates indicate that conservation buffer zone habitats can support tigers, and even areas of farming fringe when prey is conserved, highlighting the need to manage prey in conservation buffer zones. The negative road density effect ($\beta = -0.43$) supports the reported road avoidance and barrier effects, for both tigers and other large felids [22].

The lack of diel overlap in the activity patterns between the tiger and leopard ($\Delta 1 = 0.41$) is the well documented mechanism for competitive coexistence in sympatry of large felids [23]. The results from

Maharashtra are comparable with the results obtained from other parts of the Indian subcontinent and other regions of SE Asia, implying a generalizable behavioural adaptation and not a site-specific behaviour. Leopards have a wider activity range at night than tigers, which may lead to less direct competition for resources with the dominant tiger, and more resources being shared.

A critical status of Melghat-Tadoba corridor is observed (resistance score = 0.72) which is an important conservation concern for MTRN population connectivity. The dense human settlement and National Highway NH-6 along with the risk of roadkill make it almost impossible for tigers to disperse between what would otherwise be two population units that would support each other. Its route has been a history of historical dispersal events of tigers [9] and in the last decade, there have been significant drops in successful colonization attempts [8]. The Eco-passages, speed reduction measures and buffer plantation program on this corridor should be considered as a priority within the National Wildlife Action Plan.

The fact that human–wildlife conflict incidents are reduced by 68% in areas where VFC is implemented shows the effectiveness of community-based conflict mitigation measures. The same result has been found in other buffer zones of the Tiger Reserves of Corbett, Kanha, and Sundarbans [18] indicating that it is an ecologically and socioeconomically effective participatory governance model. Systematic expansion of investments in community-based insurance schemes, ex-gratia compensation schemes and livestock improvement programs are recommended throughout the MTRN landscape.

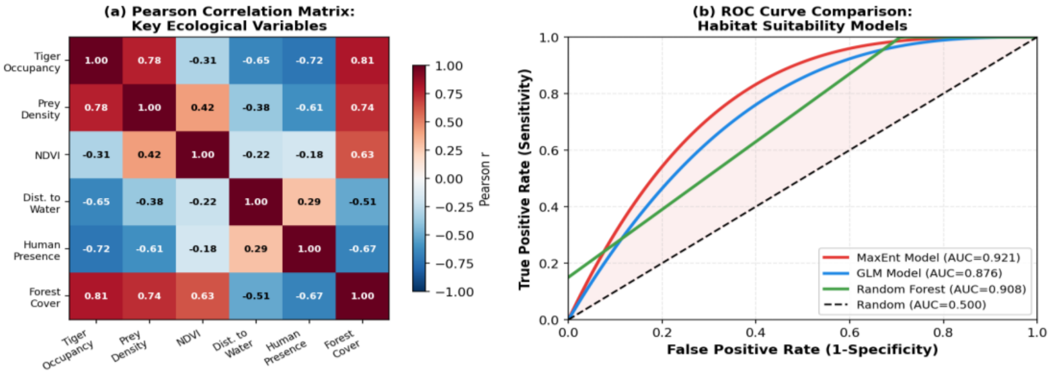

Figure 6. Statistical Modelling Outputs: (A) Pearson Correlation Matrix of Key Ecological Variables (R Values Shown; Color Scale: Blue = Negative, Red = Positive); (B) ROC Curves for Three Habitat Suitability Models (Maxent, GLM, Random Forest) with AUC Values, Demonstrating Superior Performance of Maxent for Tiger Habitat Prediction

Table 4. Occupancy Model Results: Parameter Estimates for Best-Fit Model

Covariate	Model	β Estimate	SE	z-value	p-value
Prey density (ind./km^2)	ψ(prey)	0.781	0.124	6.30	<0.001
Forest cover (%)	ψ(forest)	0.812	0.138	5.88	<0.001
Dist. to settlement (km)	ψ(settlement)	−0.651	0.108	−6.03	<0.001
Road density (km/km^2)	ψ(roads)	−0.430	0.091	−4.73	<0.001
NDVI	ψ(NDVI)	0.342	0.097	3.52	<0.001
Survey effort (nights)	p(effort)	0.218	0.064	3.41	<0.001
Season (wet vs. dry)	p(season)	−0.312	0.083	−3.76	<0.001

5. CONCLUSION

This study is the most detailed multi-year study on the ecology of apex predators and connectivity of the landscape to date in the Maharashtra Tiger Reserve Network. The key findings are: (1) forest cover continuity and prey density are the primary determinants of occupancy, and high-confidence individual identification for both species in the MTRN; (2) co-occurrence of tigers and leopards is mostly through temporal partitioning; (3) three functional wildlife corridors and three at risk/critically degraded wildlife corridors; and (4) substantial decrease in human-wildlife conflict under community-managed buffer regimes.

These results directly feed four priority management interventions: (i) restoration of emergency corridors for the Melghat-Tadoba linkage by constructing eco-passages and mitigating the highway; (ii) systematic prey management in buffer zones of Navegaon-Nagzira and Bor, to help the population to grow; (iii) scaling of the Village Forest Committee models to all five reserve units; and (iv) incorporation of satellite remote sensing-based real-time monitoring into adaptive management frameworks. A replicable, evidence-based approach and standardized methodology developed here can be used by the monitoring networks of the Central Indian Landscape and beyond.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mr. Devendra Kumar Durgam	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

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

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Informed Consent

All participants were informed about the purpose of the study, and their voluntary consent was obtained prior to data collection.

Ethical Approval

Not Applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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