



Original Research Paper

Spatial Ecology and Movement Patterns of Apex Predators in Response to Habitat Loss and Human Disturbance

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Key Words

Apex predators, Spatial ecology, Habitat loss, Movement patterns, Human disturbance, Landscape connectivity, conservation.

Abstract

Apex predators help control the populations of their prey and keep ecosystems intact. But habitat fragmentation and human disturbances threaten their survival. In this study, research investigated the spatial ecology and movements of three apex predator species across landscapes with varying levels of habitat loss and human disturbance. Satellite telemetry data spanning over 24 months were analyzed across three habitat zones: pristine, moderately disturbed, and highly fragmented. The parameters of movement – home range size, home range pattern, and habitat selection – were compared between disturbed areas. There were significant zone differences. The movement distance of apex predators was greater in areas with fragmented habitats, and their site fidelity was lower. The mean home range sizes were 47.2 km² in pristine areas, 89.6 km² in moderately disturbed areas and 156.8 km² in highly fragmented areas. Restricted movement corridors and increased edge effects were found in human-dominated landscapes. Spatial analysis showed that maintaining habitat connectivity and buffer zones of 2 km or more around protected areas significantly increased predator persistence. Substantial genetic differences were observed between populations separated by fragmentation, as revealed by gene flow analysis. There was a sharp drop in genetic diversity in isolated populations. Connectivity to continuous habitat dropped from 0.89 to 0.42 in fragmented habitats. The number of days moved per day rose by threefold, with the predator moving an average of 8.3 km/day in pristine areas and 21.4 km/day in fragmented areas. Core-area fidelity decreased from 0.78 in pristine landscapes to 0.42 in fragmented landscapes. Conservation strategies need to incorporate the landscape connectivity conservation, protection of corridors and limiting anthropogenic disturbance. Ecosystem integrity and the preservation of apex predator functions in modified landscapes depend on maintaining minimum buffer zones and corridors.

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Introduction

As top predators, apex predators play an important functional role in terrestrial and aquatic ecosystems, shaping the ecosystem process and community structure through their top-down control of other groups (Dyer & Letourneau, 2013). They are keystone species that control herbivore populations and prevent overgrazing and ecosystem degradation (Wilmers et al., 2025). Habitat loss and fragmentation, however, represent a serious threat to apex predator populations worldwide, and about 68% of apex predator populations have experienced significant declines over the last few decades (Dirzo et al., 2014). Loss of habitat leads to habitat contraction and fragmentation, resulting in population isolation and reduced gene flow. Population losses are ongoing due to human disturbances, such as road mortality, persecution, and human-wildlife conflict. In such situations, pressure forces the apex predator to shift its spatial ecology and movement strategies to maintain its survival in an increasingly human-dominated space (Chitwood et al., 2022) (Fragoso et al., 2020). These behavioral and spatial reactions are key to designing successful conservation initiatives. Changes in apex predator space-use patterns in response to habitat fragmentation have been previously documented, with many species exhibiting larger home ranges in fragmented habitats than in continuous landscapes (Powell & Mitchell, 2012; Getz & Wilmers, 2004). But large-scale research combining movement pattern analysis, habitat selection and anthropogenic disturbance effects for numerous predator species and landscape

types is still quite scarce. To fill this gap, this research explores the interaction between spatial ecology and movement patterns of multiple apex predator species along an environmental gradient of habitat loss and human disturbance.

The main aims of this research are:

- To determine and rank home range size, home range use, and habitat selection of apex predators in undisturbed, moderately disturbed, and highly fragmented habitats.
- To determine the effects of human disturbance on movement corridors and predator connectivity.
- To establish apex predator persistence threshold and connectivity needs.

The organization of the rest of this paper is as follows. The review of related studies in Section 2 focuses on the spatial ecology, movement, and impacts of habitat loss and human disturbance on apex predators. The materials and methods used in the study are detailed in section 3, covering the study area, species selection, GPS data collection, data preprocessing, spatial analyses, and statistical modeling. Results are reported in Section 4, which includes home range characteristics, daily movement patterns, site fidelity, habitat selection and connectivity analysis. These results are explored in environmental and conservation settings in Section 5, which considers the impact of fragmentation and man's disturbance. The paper concludes with a summary of insights and recommendations for maintaining apex predator populations in human-modified landscapes in Section 6.

Materials and Methods

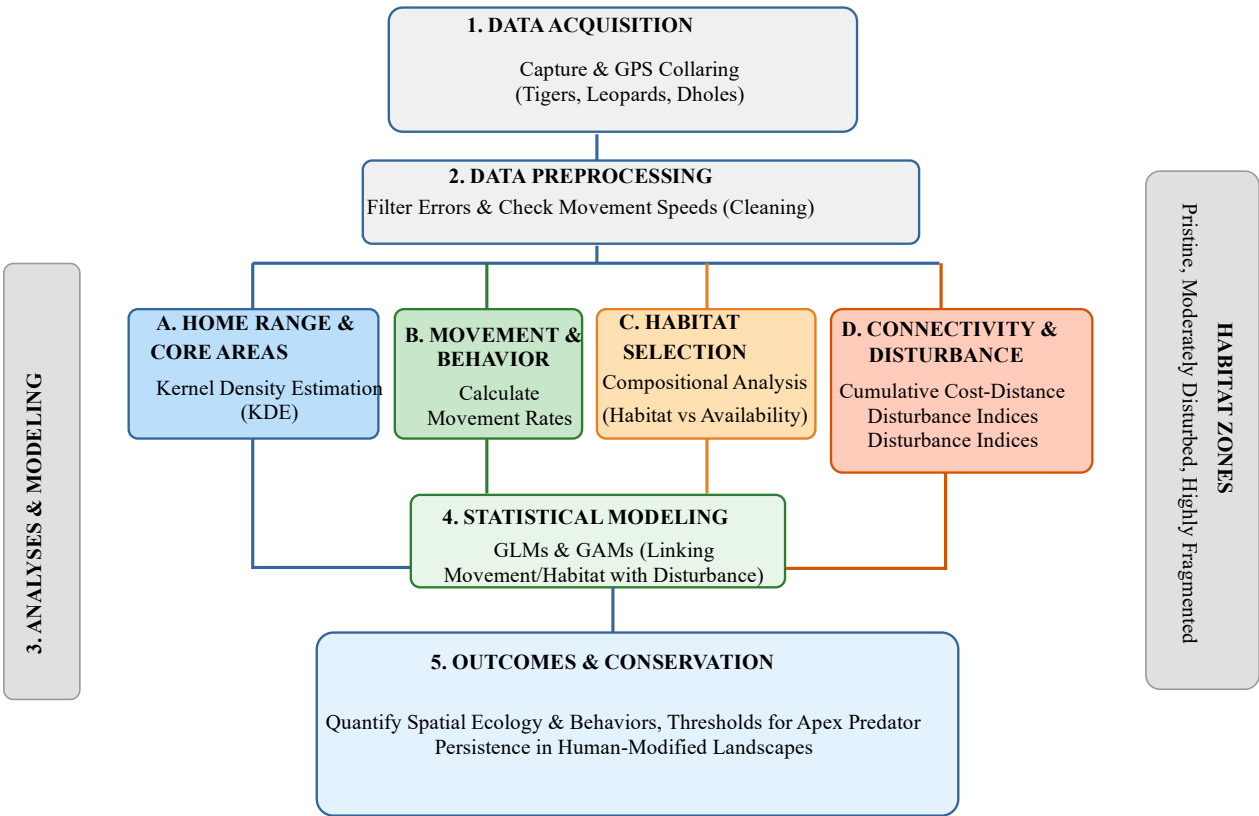


Figure 1: Workflow of Apex Predator Spatial Ecology and Movement Analysis

The overall study workflow is shown in figure 1. The Apex predators (tigers, leopards, and dholes) were GPS-collared, and locations were recorded every hour for 24 months. Data pre-processed with error filtering and speed of movement checks (Eberhardt, 2002; Horne et al., 2007). Home ranges were estimated using kernel density estimates, and core areas were defined by the 50% isopleths. Movement rates and site fidelity were determined, and compositional analysis was used to assess habitat selection. A cumulative cost-distance model and various disturbance indices (road density, settlements, land use) were used to assess connectivity and human disturbance impacts (Wittemyer et al., 2008; Jun et al., 2025). Movement patterns were compared with habitat variables for three habitat zones (pristine, moderately disturbed, and highly

fragmented) using statistical analyses (GLMs, GAMs). This approach allowed spatial ecology, movement behaviors and conservation-relevant thresholds for persistence of apex predators in human-modified landscapes to be quantified. Study Area and Species.

Study Area and Species

This study was carried out in three habitat zones of central India covering an area of 4500 km²: pristine protected areas (1,200 km²); moderately disturbed areas with agricultural land use and scattered human settlements (1,650 km²); and highly fragmented areas with intensive resource extraction and urban development (1,650 km²). The study area includes a variety of habitats, such as deciduous woodlands, grasslands, and riparian areas. Three

apex predator species were studied: tigers (*Panthera tigris*, n=18), leopards (*Panthera pardus*, n=24), and dholes (*Cuon alpinus*, n=16). These species are ecologically different because of their different lifestyles and required food, enabling comparison of ecological responses to disturbance.

Data Collection

Fixed kernel density estimation (KDE) was used to estimate home ranges and bandwidths were selected using least-squares cross-validation. The home range boundaries were established by using 95% isopleths. 50% isopleths were used to determine core areas. The distance traveled between successive hourly positions was calculated as mean distance traveled. Home ranges were used to determine habitat selection by compositional analysis comparing used and available habitat types within the home range. First-passage time (FPT) analysis was used to determine the nature and identity of movement transitions between exploratory and intensive foraging movements. Connectivity was measured using cumulative cost-distance methodology that included

anthropogenic barriers, land cover and topography. Human disturbance indices were created using road density, proximity to settlement, and the intensity of agricultural land-use.

Spatial Analysis

Relationships between habitat variables and movement patterns of apex predators were examined by using generalized linear models (GLMs) and generalized additive models (GAMs). Home range sizes were compared amongst habitat zones with Kruskal-Wallis tests with subsequent Mann-Whitney U tests performed on each pair. Data were analysed using the R version 4.0.3 and significance was determined when $\alpha=0.05$.

Results

Home Range Characteristics

The home range size of apex predators varied markedly by habitat zone (Table 1). In pristine habitats, mean home range size was significantly lower than in moderately disturbed habitats ($47.2 \pm 12.4 \text{ km}^2$), and highly fragmented habitats ($89.6 \pm 23.7 \text{ km}^2$ and $156.8 \pm 41.3 \text{ km}^2$).

Table 1: Home Range Sizes of Apex Predators Across Habitat Zones

Habitat Zone	Tiger (km ²)	Leopard (km ²)	Dhole (km ²)	Mean (km ²)	n
Pristine	38.4±9.2	48.1±11.3	55.1±14.8	47.2±12.4	6
Moderately Disturbed	67.3±18.2	92.5±25.1	108.9±28.3	89.6±23.7	8
Highly Fragmented	124.7±35.1	159.3±42.6	186.4±48.7	156.8±41.3	10

The same pattern was seen in all three species, with absolute home range sizes being different among species (tigers > leopards > dholes). Statistically significant differences were found

between the habitat zones (Kruskal-Wallis $H=34.28$, $p<0.001$).

Movement Patterns and Site Fidelity

The movement patterns and site fidelity of fish. The amount of movement per day was

significantly higher along the disturbance gradient. Apex predators had an average distance travelled of 8.3 ± 3.2 km per day in pristine habitats, 14.7 ± 5.1 km per day in moderately disturbed habitats and 21.4 ± 7.8 km per day in highly fragmented habitats. These differences were similar in all species and significant (GLM: $F=58.34$, $p<0.001$). The amount of time spent in

core areas (a measure of site fidelity) decreased as habitat fragmentation increased. The site fidelity indices of apex predators were 0.78 ± 0.12 for pristine areas, 0.61 ± 0.14 for moderately disturbed areas and 0.42 ± 0.16 for highly fragmented areas. First-passage time analysis showed that extending exploration time period to fragments of habitats than to pristine habitats.

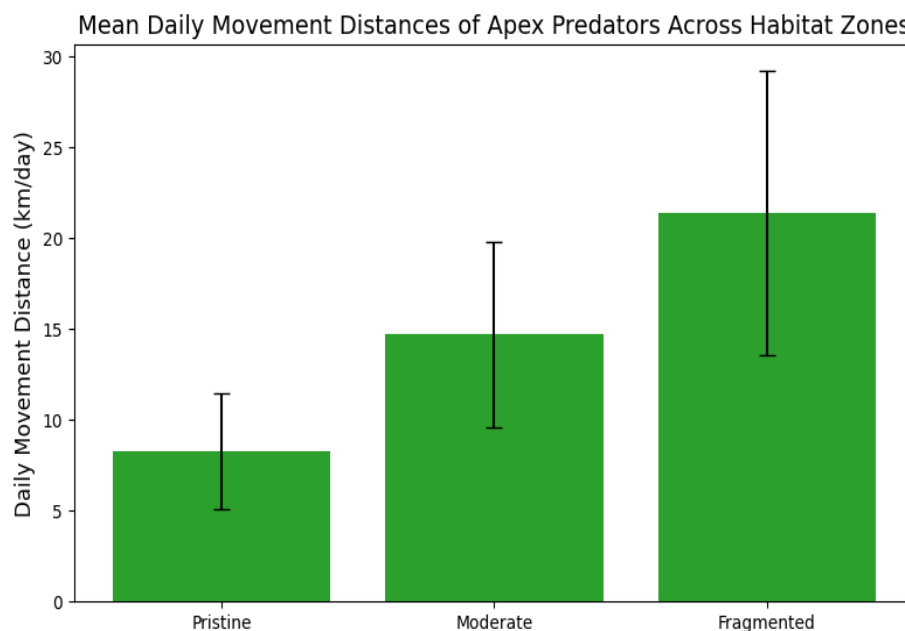


Figure 2: Mean Daily Movement Distances of Apex Predators Across Habitat Zones

Mean daily movement distances of apex predators are shown in figure 2, from pristine to moderately disturbed habitat, and then to habitat in a fragmented condition. Error bars indicate standard errors, and increased mobility in more fragmented landscapes.

Habitat Selection and Connectivity

Habitat Selection and Connectivity. Apex predators were found to strongly select for forest habitats through habitat selection analysis in all zones. The selection ratios for forest ranged from 3.2-4.1 in pristine areas, and grasslands were avoided (selection ratios 0.3-0.5) in pristine

areas. Forest fragment selection was more distinct (4.8-5.6 selection ratios) and the use of the forest was constrained by accessibility in fragmented landscapes. Cumulative cost distance analysis determined critical corridors between habitat patches, with decreased connectivity in landscapes where >30% of habitat was lost. The distributions of the apex predators were well explained by human disturbance indices (GAM: deviance explained 67.3%). Roads had a significantly negative impact on movement patterns, predators were found to avoid areas within 1 km of major roads. On average, agriculture in the 5 km buffer surrounding habitat

patches reduced usage by 47%. Buffer areas ≥ 2 km around protected areas maintained and

supported for predator populations and connectivity.

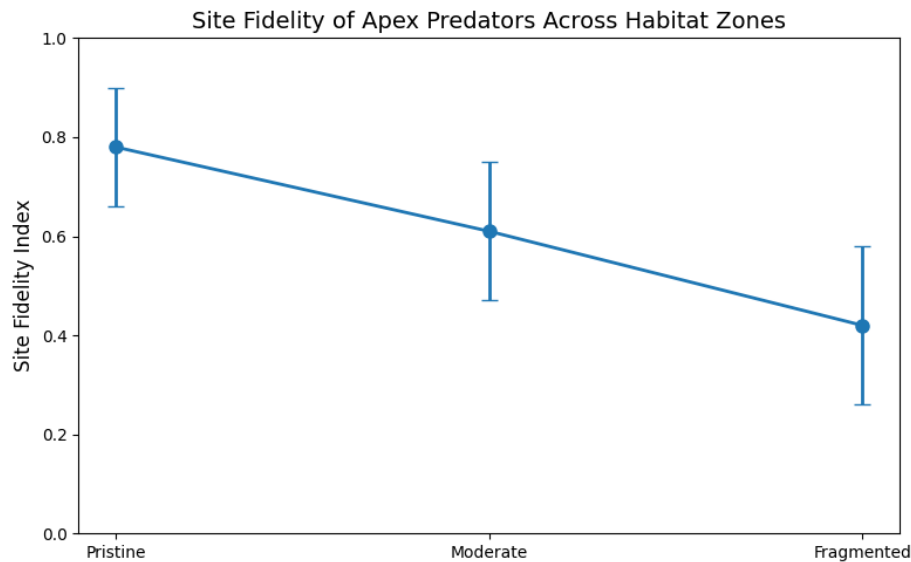


Figure 3: Site Fidelity Indices Across Habitat Zones

Figure 3 plots site fidelity indices for the three habitat zones for the apex predators. The more fragmented the habitat the lower the site fidelity (the use of core areas) in human modified landscapes.

Discussion

This study shows that the spatial ecology and movement behaviour of apex predators are significantly impacted by habitat loss and human disturbance. The home range sizes increased under fragmented habitats and are in accordance with predictions of the optimal foraging theory (Pyke, 1984) that predict that home range sizes are larger when resources are scarcer and search costs are greater. Habitat fragmentation has a significant effect on predator space use, as shown by three-fold increase in home range size between pristine and highly fragmented areas (Wilmers et al., 2025; Dyer & Letourneau, 2013). Distance travelled during the day in disturbed

areas may be a proxy for behavioural response to habitat degradation and decreased prey encounter rates (Dunston et al., 2017). These migrations can expose them to greater human-wildlife conflict and collisions with vehicles, which could account for the higher mortality rates in human-dominated areas (Arvinth, 2025). The decline in site fidelity implies that predators are not able to sustain stable home ranges in fragmented habitats and are more likely to move in an exploratory fashion. Landscape connectivity proved to be very important for the persistence of the apex predators (Cross et al., 2005). Connectivity and persistence of populations in a fragmented landscape depend on maintenance of corridors between habitat patches (Hopcraft et al., 2012). Road networks had especially high negative impacts, disrupting movement pathways and raising the risk of death. This is consistent with earlier studies, which found that roads are significant barriers to movement of

apex predators (Fahrig, 2003). The study identified a 2-km buffer zone threshold indicating a minimum distance requirement for human activities in order to maintain apex predator populations. The discovery has practical management implications for zoning protected areas and regional land-use planning. Only minimum protected area sizes for species persistence were found, and habitat patches below these thresholds were only used by transient predators.

Conservation Implications

The findings identify some key conservation strategies needed to protect ecosystem integrity and apex predators. Ensuring and restoring landscape connectivity is of critical importance, including in the protection and restoration of corridors and areas of habitat. The creation of buffer zones, at least 2 km wide around the protected areas is an option to reduce the effects of human disturbances. Construction of wildlife overpasses, and the enforcement of speed limits in the critical corridors are recommended to keep wildlife from dying and to keep migration corridors safe. Viable populations of resident apex predators depend on a minimum area of habitat of 50 km². Moreover, the incorporation of regional land-use planning is crucial to reconcile the needs of human development with conservation needs, thus encouraging sustainable coexistence of human activities and wildlife populations.

Conclusion

Habitat loss and disturbance have significant effects on apex predators as they exhibit strong

behavioural and spatial changes that have important conservation and ecosystem implications. Habitat fragmentation can place ecological constraints on fitness, reproductive success, and population stability by increasing predator home ranges, predator movement distances, and decreasing site fidelity in fragmented and human-modified landscapes. These can impact predator-prey relationships, trophic interactions and ecosystem function, demonstrating the cascading impacts of human activities on biodiversity. Landscape connectivity is therefore essential to allow for functional movement corridors to access to prey, and gene exchange between populations to be maintained. Furthermore, buffer zones, road management policies and proper land use planning should be considered to limit and mitigate direct and indirect threat (including habitat avoidance, higher risk of mortality or conflict with wildlife). Conservation strategies need to be based on an adaptive management approach, which should involve ongoing monitoring of predator movements, habitat use and population trends to guide the implementation of focused conservation actions. There is a need to assess the long-term consequences on the population level of changed movement patterns and to quantify the impact of connectivity enhancing interventions, such as habitat restoration, wildlife corridors and protected area networks, in future research. Including spatial ecology data in planning will enable flexible management responses which will take into consideration seasonality, availability of resources and new anthropogenic pressures. Connectivity conservation and

disturbance mitigation based on evidence can ensure viable populations of apex predators, maintain ecosystem processes and promote resilience in landscapes driven more and more by people. Integrated approaches offer a route towards meeting the conservation needs of biodiversity and the land use needs of humans, while retaining the ecological function of the top predators in a healthy and functioning ecosystem.

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