Population Status and Habitat Use of Golden Langur Along National Highways of Bhutan

Nature Conservation Division,
Department of Forests and Park Services,
Ministry of Energy and Natural Resources,
Royal Government of Bhutan

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Royal Government of Bhutan
Ministry of Energy and Natural Resources
Department of Forests and Park Services
DIRECTOR

FOREWORD

The Golden Langur (*Trachypithecus geei*) holds a special place in Bhutan's rich biodiversity and cultural heritage. Endemic to a small region of Bhutan and India, this primate is not only ecologically significant but also emblematic of the delicate balance between development and conservation in our landscapes. As Bhutan continues to improve its infrastructure and connectivity, especially through national highways and power transmission lines, it is essential that we assess and understand the impact of such developments on our native wildlife.

This report, ***"Population Status and Habitat Use of Golden Langur Along National Highways of Bhutan,"*** presents the first comprehensive attempt to evaluate the distribution, abundance, and occupancy patterns of Golden Langurs in relation to major road corridors across four central districts of Trongsa, Zhemgang, Sarpang, and Tsirang. The findings of this study offer vital insights into how linear infrastructure affects wildlife populations, identify critical habitat patches and interaction hotspots, and provide clear recommendations for targeted conservation interventions.

I commend the dedicated efforts of the Nature Conservation Division, including field teams from the Divisional Forest Offices and National Parks, for undertaking this important study. The integration of scientific modeling with field-based surveys makes this work not only robust but also actionable.

I trust that this report will serve as a guiding document for planners, conservation practitioners, and policymakers to ensure that development proceeds in harmony with the conservation of Bhutan's unique and endangered species.

Tashi Delek

Karma Tenzin
Director

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Royal Government of Bhutan
Ministry of Energy and Natural Resources
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NATURE CONSERVATION DIVISION
"Managing Bhutan's Natural Heritage"

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to all those who contributed to the successful completion of this Golden Langur Population and Occupancy Survey along Bhutan's National Highways. This study represents a critical step in understanding the impacts of linear infrastructure on one of Bhutan's most iconic and endangered primates.

My heartfelt appreciation goes to the focal officials and field teams from the Divisional Forest Offices of Bumthang, Tsirang, Zhemgang, and Sarpang, as well as Royal Manas National Park and Jigme Singye Wangchuck National Park. Their dedication, local knowledge, and tireless effort during field data collection were central to the success of this survey.

I also acknowledge with thanks the support of our development partners and donors, without whom this work would not have been possible. Their continued commitment to biodiversity conservation remains invaluable.

Above all, I am grateful to the local communities and forest rangers who shared valuable insights and observations, reinforcing the importance of community involvement in wildlife conservation.

Sonam Wangdi
Chief Forestry Officer

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EXECUTIVE SUMMARY

This report presents the first integrated analysis of Golden Langur (*Trachypithecus geei*) populations, habitat use, and conservation threats along Bhutan's national highways. Based on field surveys conducted over ten separate occasions (days), the study assessed species capture rates, population demographics, site-specific abundance, and habitat occupancy across seven highway segments that traverse key Golden Langur landscapes. The estimated total population of Golden Langurs along these highways is approximately 1,908 individuals (±162 SE; 95% CI: 1,617–2,256). The population is female-biased, with around 566 females, 312 males, and 485 juveniles, indicating a demographically stable and actively reproducing population. Capture rates and population estimates varied significantly among corridors, with the highest densities observed along Langthel–Trongsa, Tingtibi–Pantang, and Tingtibi–Zhemgang–Wangdigang highways. Conversely, corridors such as Gelephu–Tsachhu recorded lower population sizes and capture frequencies, likely due to fragmented habitats and anthropogenic pressures.

Occupancy modeling identified forest cover as the strongest predictor of Golden Langur habitat use. Models incorporating elevation and river proximity showed limited explanatory power, reinforcing the species' strong dependence on intact forest canopies for movement, feeding, and reproduction. Occupancy probabilities were highest in well-forested corridors such as Gelephu–Tsirang and Tingtibi–Pantang, while degraded corridors exhibited lower habitat use, underscoring the importance of maintaining continuous canopy cover to support the species. Spatial mapping of occupancy probability confirmed that forest-rich segments offer the most suitable habitats, while areas affected by deforestation, settlement expansion, and road development represent ecological bottlenecks.

The study also highlighted multiple anthropogenic threats that jeopardize langur populations along highways. These include roadkill incidents, electrocution from powerlines, habitat fragmentation due to development activities, and the potential for hybridization with closely related species in border areas. Some corridors are at risk of becoming population sinks due to isolation and reduced gene flow, particularly where canopy connectivity has been compromised. These findings indicate an urgent need to mitigate infrastructure-related threats and restore degraded habitats to preserve population viability and ensure long-term connectivity between subpopulations.

To address these challenges, the report recommends several targeted conservation actions. These include habitat restoration in fragmented areas, installation of canopy bridges to facilitate safe arboreal movement, and retrofitting of power infrastructure to prevent electrocution. Engaging local communities in corridor monitoring, stray dog management, and eco-tourism initiatives is also emphasized to foster stewardship and reduce human-wildlife conflict. In addition, the integration of habitat use maps into environmental impact assessments and the enforcement of wildlife protection laws are critical policy measures. Long-term monitoring and genetic research are recommended to track changes in occupancy, assess population health, and evaluate the effectiveness of conservation interventions.

In conclusion, the study demonstrates that Bhutan’s national highways support viable Golden Langur populations, particularly in forested corridors that serve as extensions of nearby protected areas. However, increasing development pressure poses growing risks to habitat connectivity and demographic stability. By aligning with the Golden Langur Conservation Strategy and Action Plan (July 2025– June 2035), the findings provide an evidence-based framework for managing habitat corridors, guiding restoration efforts, and informing infrastructure development in ways that ensure the species’ long-term survival in Bhutan’s rapidly changing landscape.

CHAPTER 1

INTRODUCTION

Golden langur (*Trachypithecus geei*) is “Endangered (EN)” colobine monkey where its distribution is restricted to Bhutan and Northeast India (Das et al., 2008). In Bhutan it is found in the forested habitats of Sarpang, Trongsa, Tsirang, and Zhemgang dzongkhags (districts) with total area of around 3484 km^2 as shown in Figure 1.1 (Thinley et al., 2020). Its suitable habitat in Bhutan expands across 34 geogs (village blocks of district), within the six dzongkhangs of Dagana, Sarpang, Trongsa, Tsirang, Wangduephodrang, and Zhemgang (Choudhury, 2001; Thinley et al., 2020). A recent population estimate indicates that Bhutan's golden langur population is now 2,516 ± 363 individuals per square kilometer, which represents less than half of the 6,637 individuals estimated in 2005 (Thinley et al., 2019; Wangchuk, 2005).

More than 54% of the golden langur in previous surveys were located inside three protected areas of Bhutan, Jigme Singye Wangchuck Naitonal Park (JSWNP), Phibsoo Wildlife Sanctuary (PWS) and Royal Manas National Park (RMNP) that covers only 33% of the total suitable area in Bhutan (Thinley et al., 2020). In India, it is distributed in fragmented landscapes covering area about 3950 km^2 in the Chirang, Kokrajhar, Dhubri and Bongaigoan districts of Assam (Chatterjee et al., 2022; Choudhury, 1992). Golden langurs were usually isolated in the transboundary landscape of Bhutan and India, but several bridge constructions over the major rivers including Mangdechhu river might have favored geographical expansion breaking the barriers. It might have also favored the hybridization between sympatric species such as Assamese macaque (*Macaca assamensis*) and rhesus macaque (*Macaca mulatta*) (Thinley et al., 2020; Wangchuk, 2005).

Although the golden langur is classified as a protected species under Schedule II of the Forest and Nature Conservation Act of Bhutan 2023, and Schedule I of the Wildlife Act of India, their survival is severely threatened by habitat fragmentation (Roy & Nagarajan, 2018). In Bhutan a study reported total of 107 incidences of golden langur mortality and injury from anthropogenic activities. Of all almost 46.7% are due to electrocution followed by 28% road kills, 14% dog kills, 5.6% retaliatory killing, 3.7% road injuries and 1.9% pet keeping (Thinley et al., 2020). The threat ranking revealed hydropower, road, and housing development as topmost threat to golden langur followed by agriculture expansion and resource extraction as medium threat (Thinley et al., 2020). Pet keeping, retaliatory killing and hybridization with other genetically compatible langurs are treated as low threat (Thinley et al., 2020). Road kills and electrocution are threats that require immediate attentions for the mitigation, and most of road kills occurs along Gelephu-Sarpang road and Dakphel-Zhemgang road, and Dakphel-Tingtibi road (Thinley et al., 2020). These findings were based on interviews with local mass, group discussion with the forestry staff in the field and social media interview requiring further ground truthing.

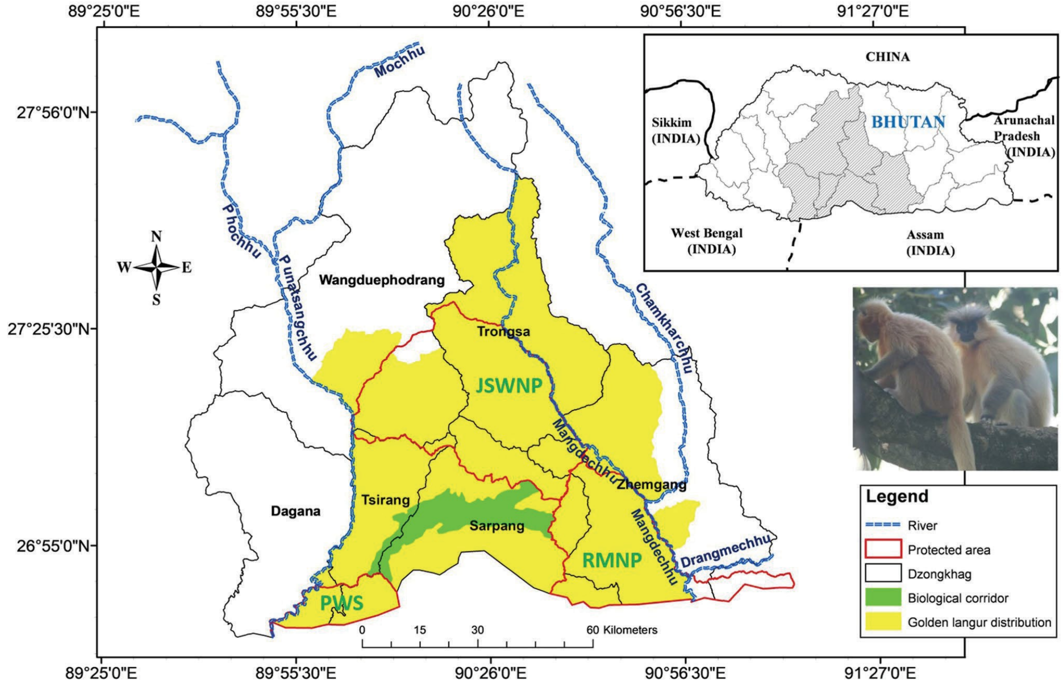


Figure 1. The map showing distribution of golden langur in different districts and protected areas of Bhutan. The inset map shows location of Bhutan relative to the neighboring country and the shaded portion represents the distribution of golden langur. (Thinley et al., 2020)

Understanding the population dynamics of Golden Langurs in areas adjacent to roads, high-voltage road, electric transmission lines, and human settlements is critical for mitigating anthropogenic threats. Such knowledge is essential for identifying high-risk zones where Golden Langur fatalities and human-langur conflicts are likely to occur. This study aims to systematically identify hotspots of human–Golden Langur interactions along major infrastructure corridors, including highways and transmission lines, as well as peri-urban areas. The findings will not only help reduce threats but also promote coexistence through conservation-based tourism, highlighting the ecological and cultural value of Golden Langurs.

The main objectives of our study are:

1. To assess the distribution and population density of Golden Langurs in proximity to major highways of Bhutan.
2. To identify key interaction hotspots where human–Golden Langur encounters are frequent, particularly along highways.
3. To explore sustainable tourism opportunities centered on Golden Langurs that promote positive interactions and generate local conservation incentives.
4. To utilize empirical data to guide the development of targeted mitigation strategies, reducing mortality and habitat disturbance due to anthropogenic activities.

CHAPTER 2
MATERIALS AND METHODS

2.1. Study Area

The study was conducted along key highway corridors traversing the districts of Trongsa, Zhemgang, Sarpang, and Tsirang in south-central Bhutan (Figure 2.1). These highways were selected based on historical records and prior studies indicating frequent roadkill incidents and high levels of anthropogenic threats to Golden Langurs (Dorji et al., 2021; Thinley et al., 2019). Local forest rangers from Divisional Forest Office and park offices had also documented regular sightings and conflict incidents along these routes. The highways intersect two critical protected areas—Royal Manas National Park (RMNP) and Jigme Singye Wangchuck National Park (JSWNP)—providing important ecological connectivity between core habitats. Notably, we excluded farm roads in Dagana and Wangduephodrang districts, as past observations and field reports indicated relatively lower threats in these areas compared to the main highway corridors. In this study, a combined 418 kilometers of primary and secondary national highways were surveyed across Bhutan (Figure 2.1).

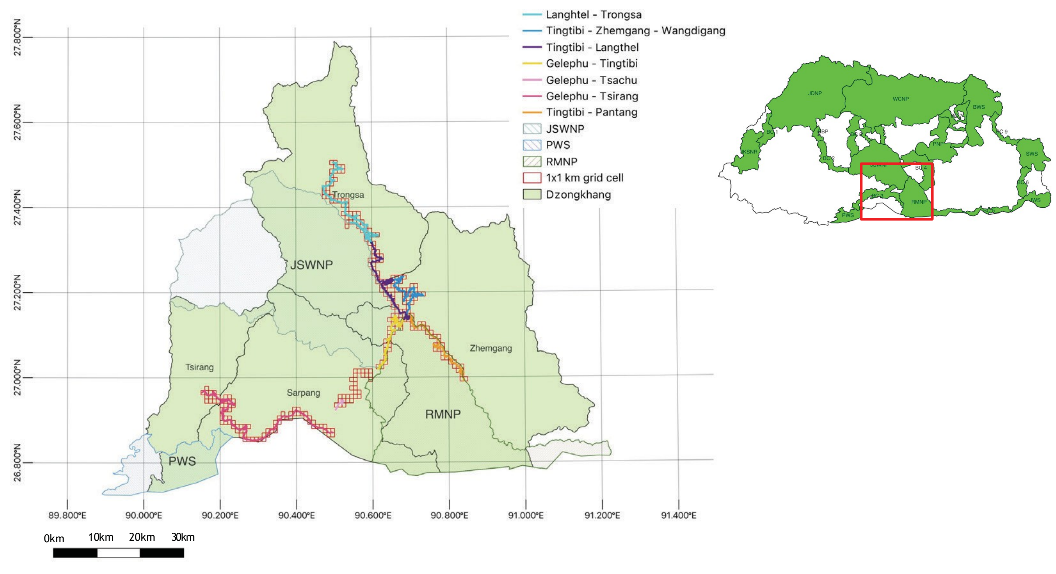


Figure 2.1. Map of the survey area showing sampling sites along Bhutan's national highways. The 1×1 km grid cells represent the designated sampling units used for Golden Langur population surveys.

2.2. Field Survey

To assess Golden Langur presence along Bhutan's national highways, the entire highway stretch within the study area was divided into 312 sampling units, each measuring 1 × 1 km (Figure 2.1). This grid size was selected based on the species' known home range, which typically falls below 1 km², allowing each grid to serve as an effective proxy for a single Golden Langur group's territory (Rekha Chetry et al., 2017; Roy & Nagarajan, 2018).

Field surveys were conducted through transect drives along these grids, jointly undertaken by teams from the Divisional Forest Offices of Bumthang, Tsirang, Sarpang, and Zhemgang, as well as staff from Royal Manas National Park and Jigme Singye Wangchuck National Park. Each transect was driven twice daily from 6:00 to 8:00 AM and 4:00 to 6:00 PM, coinciding with the species' peak activity and feeding periods (Biswas et al., 2024; Chakravarty & Saikia, 2023; Dorji et al., 2021). During each transect, the team recorded all Golden Langurs observed above and below the highway—within approximately 1 km of the road corridor—that were visible through direct ocular counts. Daily sightings were treated as independent detection occasions, and surveys were repeated over 10 consecutive days to improve detection probability and generate reliable encounter histories (Keane et al., 2011; McLachlan et al., 2019).

2.3. Preparation of covariates

To model the occupancy and abundance of golden langurs along Bhutan's national highways, we prepared three key site-level covariates: forest cover, elevation, and distance to the nearest river. Each covariate was extracted for all 312 sampling units by taking 1km buffer from highway. Forest cover, a critical variable for this arboreal species, was derived from the Hansen et al. (2013) Global Forest Change dataset, which provides tree canopy cover estimates at 30-meter resolution (Hansen et al., 2013). We calculated the mean percentage canopy cover within each grid using zonal statistics in QGIS, representing forest availability at the landscape scale (Q. D. Team, 2025). Elevation data were obtained from a Digital Elevation Model (DEM) and averaged for each grid cell to account for altitudinal habitat variation. To assess proximity to water sources, we calculated the Euclidean distance (in meters) from each grid centroid to the nearest river using the national hydrological layer. All covariates were extracted and processed using QGIS and R (using packages raster, sf, and exactextractr) (Baston, 2023; Hijmans et al., 2015; Pebesma, 2023), and were standardized (centered and scaled) prior to modeling to ensure comparability and model stability (Stanton Jr et al., 2015). These covariates were then used to parameterize both occupancy and N-mixture abundance models in the unmarked package in R.

2.4. Abundance Estimation

2.4.1. Total Count

We conducted total population count for estimating the number of golden langurs that resides near the highway as the survey area is relatively small compared to the total distribution range of golden langur. Total count method is followed under following condition: (1) when the area to be surveyed is relatively small so that the whole area can be searched, (2) the species can be easily found and identified, (3) the number of animals to be counted is not more than about 500, and (4) individuals or groups can be recognized and separated from others (Plumptre et al., 2013). As vehicular traffic is proportionately higher on national highways than the feeder road or farm roads in Bhutan, we selected the survey site along national highways passing through the golden langur habitat (Figure 2.1). We consider this highway as a survey site rather than a transact and recorded observation of golden langur along this highway for 10 consecutive days using survey form of annexure I to fulfill repeated count by occupancy modelling (MacKenzie et al., 2003).

2.4.2. Data analysis

To estimate the abundance of Golden Langurs along each highway corridor, we applied a Maximum Likelihood-based N-mixture model using the unmarked package in R (Fiske & Chandler, 2011; R. C. Team, 2025). This model is well-suited to our survey design, which involved repeated counts at spatially replicated sampling sites (McLachlan et al., 2019; McLachlan & Peel, 2000). N-mixture models allow estimation of species abundance while accounting for imperfect detection, thus providing more reliable insights into population status across the landscape (Joseph et al., 2009).

In this framework, the true abundance at each site (N_i) is treated as a latent (unobserved) variable, assumed to follow a Poisson distribution with mean expected abundance λ_i (Kéry & Royle, 2020). The observed count (C_{ij}) during visit *j* at site *i* is modeled as a binomial random variable conditional on N_i and detection probability p (Kéry & Royle, 2020). The general form of the N-mixture model is:

$$\text{State model:} \quad N_i \sim \mathit{Poisson}(\lambda_i)$$

$$\text{Observation model:} \quad C_{ij} \sim \mathit{Binomial}\,(N_i, p)$$

To explore the influence of environmental variables on abundance, we modeled λ_i as a function of site-specific covariates—Forest Cover, Elevation, and Distance to River—using a log-link function:

$$\log(\lambda_i) = \beta_0 + \beta_1 \cdot Forest_i + \beta_2 \cdot Elevation_i + \beta_3 \cdot River_i$$

Here, β_0 is the intercept, and β_1–β_3 are the estimated coefficients for each covariate. For detection probability, we assumed it to be constant across repeated visits, such that:

$$\mathrm{logit}(p_{ij}) = \alpha_0$$

The model was fitted using the *pcount* function in the “unmarked” package, incorporating model selection, parameter estimation, and prediction of abundance (Fiske & Chandler, 2011). This approach enabled us to identify environmental drivers of abundance while correcting for detection bias, ultimately supporting spatially explicit conservation planning for Golden Langurs along Bhutan’s highway corridors.

To identify the most parsimonious model for estimating Golden Langur abundance, we constructed 8 candidate set of N-mixture models incorporating various combinations of ecological covariates hypothesized to influence abundance (Table 2.1): Forest Cover, Elevation, and Distance to River. All models assumed constant detection probability across visits. We compared models using Akaike’s Information Criterion (AIC), which balances model fit and complexity (Burnham & Anderson, 2004). The model with the lowest AIC value was selected as the best-supported model, while models within $\Delta AIC < 2$ were considered to have substantial support. Models with higher ΔAIC were deemed less informative.

Table 2.1. Candidate model for abundance estimation and model specification considering constant probability of detection across the survey area.

Model ID	Abundance Formula	Detection Formula	Description
mod0	$\lambda \sim 1$	$p \sim 1$	Null model (intercept-only)
mod1	$\lambda \sim$ Elevation	$p \sim 1$	Effect of elevation
mod2	$\lambda \sim$ Forest	$p \sim 1$	Effect of forest cover
mod3	$\lambda \sim$ River	$p \sim 1$	Effect of distance to river
mod4	$\lambda \sim$ Elevation + Forest + River	$p \sim 1$	Full additive model with all covariates
mod5	$\lambda \sim$ Forest + River	$p \sim 1$	Combined effect of forest and river
mod6	$\lambda \sim$ Elevation + River	$p \sim 1$	Combined effect of elevation and river
mod7	$\lambda \sim$ Elevation + Forest	$p \sim 1$	Combined effect of elevation and forest

2.5. Habitat uses by Golden Langur

To assess habitat use patterns of Golden Langurs (Trachypithecus geei) along Bhutan's national highways, we employed a single-season occupancy modeling framework using the unmarked package in R (Fiske & Chandler, 2011). This approach is designed to estimate two key parameters:

ψ: the probability that a site is occupied by the species, and

p: the probability of detecting the species during a survey, conditional on its presence.

This framework is particularly useful when detection is imperfect, as is typical in forested environments with cryptic arboreal species like golden langurs (Bailey et al., 2014; MacKenzie et al., 2009).

The occupancy modeling framework consists of two components:

1. State (Ecological) Process – modeling the true presence or absence of the species:

$$Z_i \sim Bernoulli(\psi_i)$$

where Z_i is the latent occupancy state (1 = occupied, 0 = unoccupied) for site i, and ψ_i is the probability that site i is occupied.

2. Observation Process – modeling detections conditional on presence:

$$Y_{ij} \sim Bernoulli(Z_i \times p_{ij})$$

where Y_{ij} is the detection (1 = detected, 0 = not detected) at site i on survey occasion j, and p_{ij} is the detection probability for that visit.

We modeled occupancy probability (ψ_i) as a function of three site-level covariates: Forest cover (% canopy cover), Elevation (meters above sea level) and Distance to the nearest river (meters)

The logit-linear form of the occupancy model is:

$$logit(\psi_i) = \beta_0 + \beta_1 \times Forest_i + \beta_2 \times Elevation_i + \beta_3 \times River_i$$

Detection probability was assumed to be constant across all sites and occasions:

$$logit(p_{ij}) = \alpha_0$$

To identify the best-supported model structure for estimating Golden Langur occupancy, we developed five a priori candidate models incorporating ecologically meaningful covariate combinations. These included a null model with no covariates (m0), a univariate model with elevation (m1), a univariate model with forest cover (m2), a univariate model with river proximity (m3), and a full additive model including elevation, forest cover, and river distance (m4). In all models, detection probability was held constant across sites and survey occasions. We used Akaike's Information Criterion (AIC) to evaluate model performance, selecting the model with the lowest AIC as the best-supported (Burnham & Anderson, 2004). Models with ΔAIC less than 2 were considered to have substantial support, indicating comparable explanatory power. This approach enabled us to assess the relative importance of each environmental covariate in influencing Golden Langur habitat use along Bhutan's highway corridors.

CHAPTER 3

RESULTS

3.2. Golden Langur Capture Rates by Highway

Golden langur capture rates varied considerably across surveyed highways over the period of 10 survey occasions (days), indicating differences in habitat quality, group density, and landscape connectivity. Langthel–Trongsa recorded the highest capture frequency with 80 events and 1,351 individuals, averaging nearly 17 per event, suggesting a high-density population along this corridor. Similarly, Tingtibi–Pantang accounted for 83 events with 893 individuals, while Tingtibi–Zhemgang–Wangdigang documented 1,135 individuals across 78 events, averaging over 14 individuals per event. In contrast, Gelephu–Tsirang reported the lowest mean capture rate of 8.7 individuals per event despite 28 records, indicating reduced detectability. Gelephu–Tsachu and Gelephu–Tingtibi showed moderate capture rates, with averages of approximately 12 individuals per event as shown in Table 3.1.

Table 3.1. Capture rates of golden langur along different highways (Capture events is total record of golden langur over a period of 10 survey occasions; Total captures are number of golden langurs recorded in 10 survey occasions)

Highway	Survey Area Km^2	Distance in km	Capture Events	Total Captures	Mean per Event
Gelephu - Tingtibi	50.14	94	27	324	12.00
Gelephu - Tsachu	12.148	23	13	166	12.77
Gelephu - Tsirang	129.002	104	28	245	8.75
Langthel - Trongsa	86.363	47	80	1351	16.89
Tingtibi - Langthel	74.171	50	28	359	12.82
Tingtibi - Pantang	72.677	47	83	893	10.76
Tingtibi - Zhemgang - Wangdigang	41.431	53	78	1135	14.55

3.2. Golden Langur Populations Along Bhutan’s National Highways

3.2.1. Population model

Eight candidate models were compared using AICc to determine the best-fitting model. The model including elevation, forest cover, and river proximity had the lowest AICc (22018.79) and the highest AICc weight, indicating the greatest likelihood of being the best approximating model. It was selected as the most parsimonious model for site specific abundance estimation. The next-best model (forest + river) had a ΔAICc of 4.68, which is above the commonly accepted threshold (ΔAICc ≤ 2) for substantial support (Burnham & Anderson, 2004). All other models had ΔAICc > 18, providing little to no support as shown in Table 3.2.

Table 3.2. Model Ranking Based on AICc

Model (Covariates)	**K**	**AICc**	**ΔAICc**
Elevation + Forest cover+ River distance	5	22018.79	0.00
Forest cover + River distance	4	22023.47	4.68
Elevation + Forest cover	4	22036.92	18.13
Forest cover only	3	22043.86	25.07
River distance only	3	22209.47	190.68
Elevation + River distance	4	22210.06	191.27
Null (Intercept only)	2	22212.45	193.66
Elevation only	3	22213.78	194.99

3.2.2. Overall Population of Golden Langurs Along Bhutan’s National Highways

The overall estimated population of golden langurs occupying Bhutan’s national highways comprises approximately 1,908 (±162 SE; 95% CI: 1,617–2,256) individuals. Among these, females were the most abundant, with an estimated 566 individuals (95% CI: 483–663), reflecting a healthy reproductive base. Juveniles accounted for 485 individuals (95% CI: 411–573), indicating ongoing recruitment and a stable demographic structure. The male population was lower, with 312 individuals (95% CI: 249–394), consistent with the species’ typical social organization where fewer adult males are present in multi-female groups. Additionally, 545 individuals (95% CI: 474–627) could not be sexed during field observations due to visibility constraints or behavioural factors (escaping human encounter, high on the tree canopy).

This overall composition suggests a female-biased population structure with a significant juvenile proportion, supporting the likelihood of an actively reproducing and stable population along surveyed corridors (Figure 3.1).

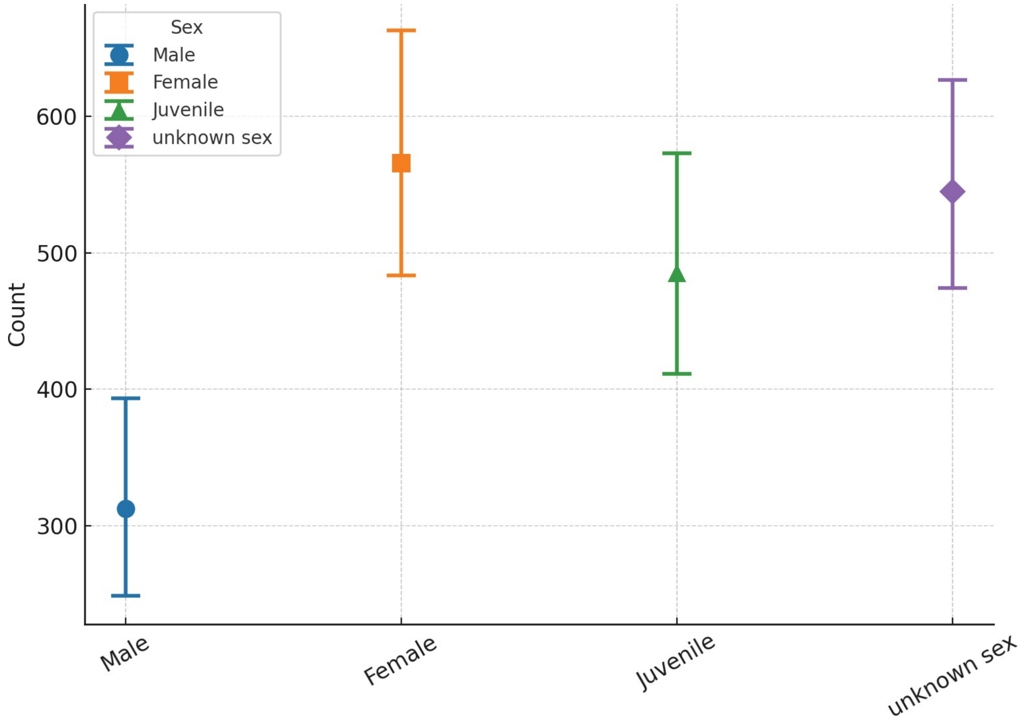


Figure 3.1. Graph illustrating sex-specific population estimates of golden langurs, including juveniles, along Bhutan's national highways. Error bars represent the 95% confidence intervals of the estimates.

3.2.3. Site-Specific Golden Langur Population Estimate

Golden langur populations showed marked variation across the surveyed highway corridors, reflecting differences in habitat quality, forest connectivity, and potential human disturbance (Table 3.3; Figure 3.2). The Gelephu–Tsirang corridor recorded the highest population estimate (≈456 individuals), suggesting a key population stronghold with well-connected forests and favourable habitat conditions though overall detection was lower compared to rest of the site. Similarly, Tingtibi–Pantang (≈343 individuals) and Tingtibi–Langthel (≈321 individuals) supported substantial numbers, reinforcing their importance as high-density habitats.

Langthel–Trongsa (≈299 individuals) also maintained a healthy population, likely due to its continuous forest canopy and proximity to core protected areas. In contrast, Gelephu–Tingtibi Highway (≈247 individuals) and Tingtibi–Zhemgang–Wangdigang (≈187 individuals) had moderate estimates, possibly influenced by habitat fragmentation, edge effects, or higher human activity. The lowest population was recorded along Gelephu–Tsachhu (≈54 individuals), indicating either marginal habitat suitability or smaller, isolated groups.

Table 3.3. *Site-specific golden langur population estimates, including sex-wise composition, across seven highway corridors: 1 – Gelephu–Tsachu; 2 – Gelephu–Tsirang; 3 – Gelephu–Tingtibi; 4 – Langthel–Trongsa; 5 – Tingtibi–Langthel; 6 – Tingtibi–Pantang; and 7 – Tingtibi–Zhemgang–Wangdigang.*

Highway	Males (95% CI)	Females (95% CI)	Juveniles (95% CI)	Unknown (95% CI)	Total Estimate
1	10 (8–12)	15 (13–17)	13 (11–15)	12 (10–14)	~50
2	78 (62–100)	140 (130–150)	130 (115–140)	120 (110–130)	~470
2	35 (28–43)	60 (55–66)	65 (55–75)	78 (68–88)	~238
3	50 (40–65)	80 (72–95)	75 (68–90)	100 (85–115)	~305
4	55 (45–68)	90 (82–105)	80 (72–90)	95 (85–110)	~320
5	65 (55–75)	110 (98–120)	100 (85–110)	90 (80–100)	~365
6	19 (15–25)	71 (61–82)	102 (90–114)	150 (130–170)	~342
Total	**312**	**566**	**485**	**545**	**1,908**

Within these sites, females consistently outnumbered males, and juveniles formed a significant proportion, suggesting ongoing reproduction in most corridors. Sites with higher juvenile proportions indicate potential recruitment hotspots, while areas with fewer juveniles may signal reduced reproductive success.

3.2.4. Population Trend and Analysis

Although this survey represents a single population assessment and does not provide long-term trends, several key patterns are evident. The golden langur population along Bhutan's highway corridors shows a female-biased structure, with an estimated 566 females compared to 312 males, resulting in a sex ratio of approximately 1.8:1. This aligns with the species' typical social organization, where groups are primarily composed of multiple females with a limited number of males (R. Chetry et al., 2017). Juveniles make up around 25% of the population (485 individuals), suggesting active reproduction and stable recruitment across most sites. The lower male representation may be due to natural group composition, differential detectability of solitary males, or sex-specific habitat preferences.

Spatially, Gelephu–Tsirang and Tingtibi–Pantang exhibited the highest population densities, indicating well-connected forests and high-quality habitats that support stable groups. Conversely, Gelephu–Tsachhu and Tingtibi–Zhemgang–Wangdigang recorded smaller populations, which may reflect habitat fragmentation, anthropogenic disturbance, or the presence of smaller, isolated groups (Figure 3.2). Notably, some sites, such as Zhemgang–Wangdigang, had a high proportion of individuals categorized as unknown sex, highlighting observational challenges during field surveys. Overall, the population structure suggests a stable and reproducing population, yet site-specific variation emphasizes the need for targeted conservation efforts to maintain habitat connectivity and improve monitoring accuracy.

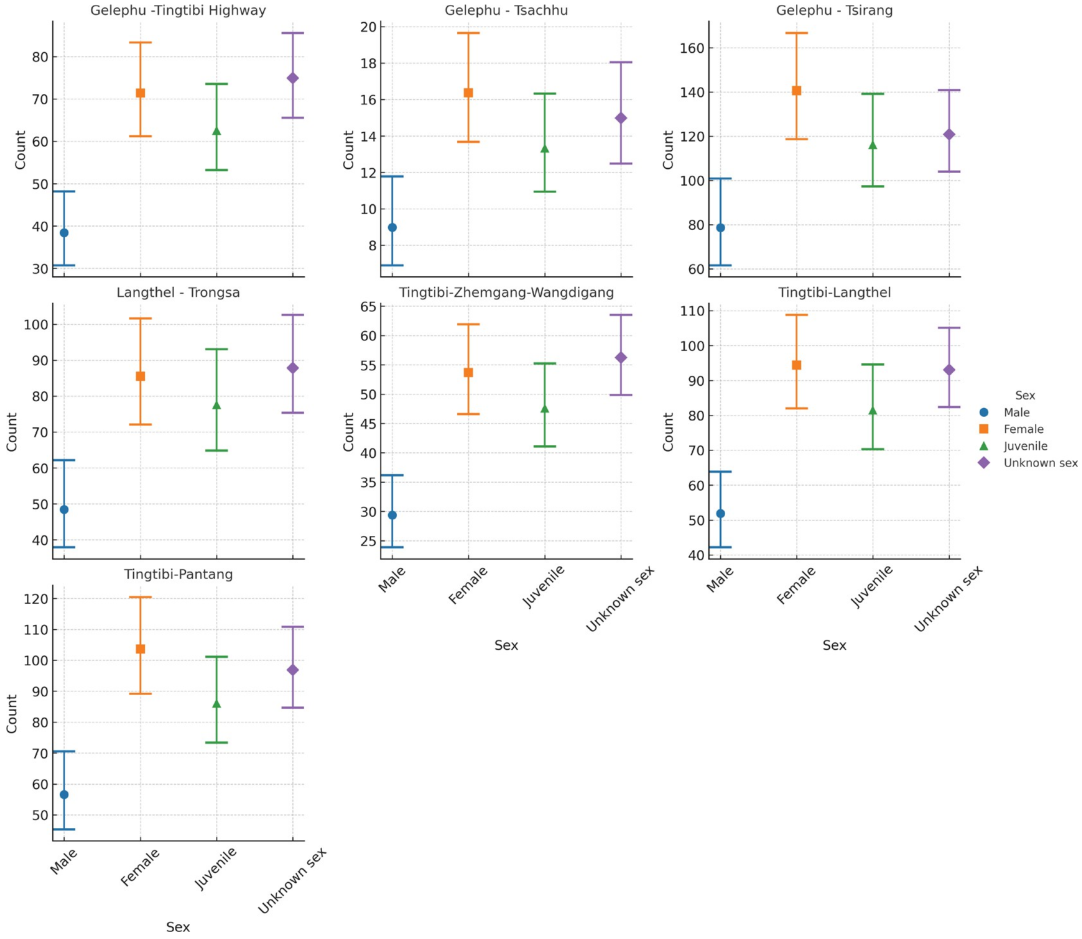


Figure 3.2. Graph illustrating sex-specific population estimates of golden langurs, including juveniles, along 7 highways along golden langur habitat of Bhutan. Error bars represent the 95% confidence intervals of the estimates.

3.3. Habitat use by Golden Langur Along Bhutan's National Highways

3.3.1. Optimal model for predicting Golden Langur habitat use

Model selection based on Akaike's Information Criterion (AIC) indicated that forest cover was the most important predictor of Golden Langur occupancy. The forest cover model ($\psi \sim$ forest) ranked highest (AIC = 1626.45, ΔAIC = 0.00, AIC weight = 0.75), carrying the majority of the model weight. The full additive model ($\psi \sim$ elevation + forest + river) was the second-best model (AIC = 1628.69, ΔAIC = 2.24, weight = 0.25), suggesting that additional covariates provided only marginal improvement.

The null model ($\psi \sim 1$), elevation-only model ($\psi \sim$ elevation), and river proximity model ($\psi \sim$ river) performed substantially worse, with ΔAIC values > 12 and negligible model weights (<0.002), indicating weak support for elevation and river effects on occupancy.

Table 3.4. Model selection results for the scale-optimized multivariate occupancy models assessing Golden Langur habitat use probability along Bhutan's National Highways.

Model	k	AIC	delta	AICwt
~1 ~ forest (Forest cover effect)	3	1626.45	0	0.75167
~1 ~ ele + forest + river (Full additive model)	5	1628.69	2.24	0.24514
~1 ~ 1 (Null model)	2	1638.47	12.02	0.00184
~1 ~ river (River proximity effect)	3	1640.47	14.02	0.00068
~1 ~ ele (Elevation effect)	3	1640.49	14.04	0.00067

3.3.2. Covariate effects on occupancy of Golden Langur

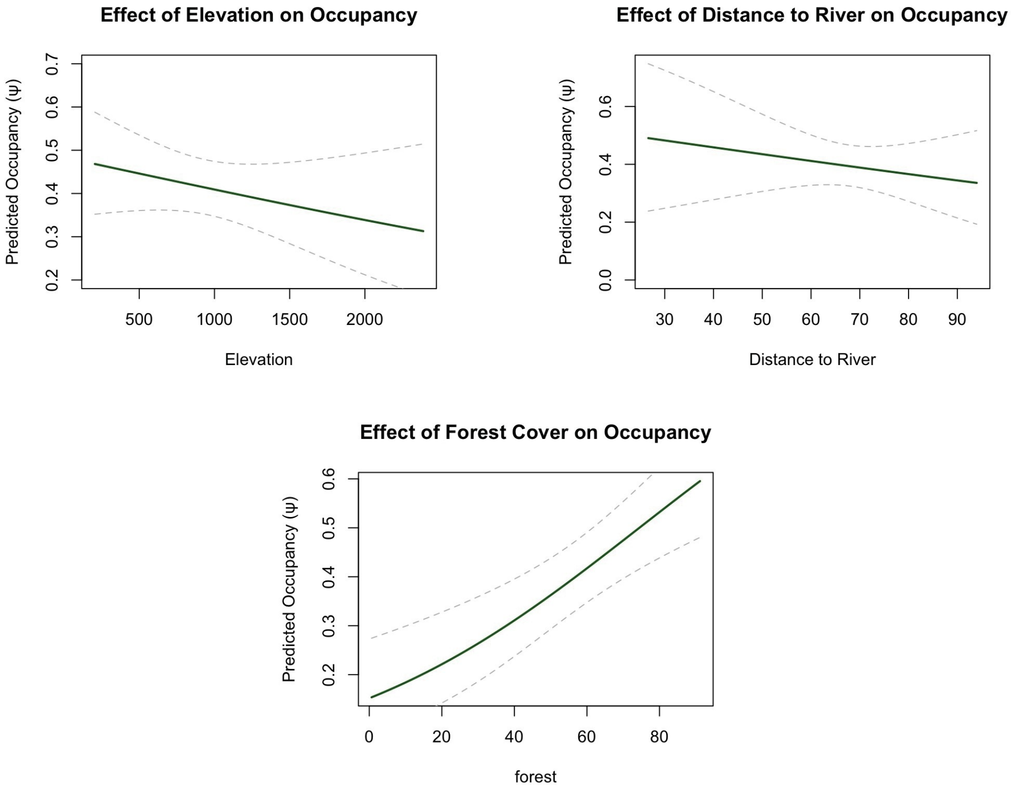
The occupancy modeling results highlight the influence of habitat covariates on Golden Langur habitat use along Bhutan's National Highways. Among the tested models, forest cover emerged as the strongest predictor of Golden Langur occupancy. In the single-covariate model ($\psi \sim$ forest), the forest cover coefficient was positive and significant ($\beta = 0.0199$; 95% CI: 0.0091–0.0308), indicating that the probability of site occupancy increased with greater forest cover. This result supports the species' strong association with intact and continuous forest habitat.

The full additive model (ψ ~ elevation + forest + river) retained forest cover as a significant covariate (β = 0.0231; 95% CI: 0.0117–0.0345), while elevation (β = -0.0003; 95% CI: -0.0009–0.0003) and river proximity (β = -0.0096; 95% CI: -0.0359–0.0167) had negligible effects with confidence intervals overlapping zero. This suggests that within the sampled elevation range and river network, these factors are not strong determinants of Golden Langur habitat use.

Null and single-covariate models for elevation and river proximity showed weak performance, with occupancy intercepts close to zero and wide confidence intervals. The river-only model indicated almost no effect of proximity to rivers (β ≈ 0), while the elevation-only model similarly showed no clear directional effect. Overall, these findings indicate that forest cover is the primary driver of Golden Langur habitat use, underscoring the importance of maintaining forested landscapes to support their persistence along road corridors.

Table 3.5. Parameter estimates for occupancy models of Golden Langur habitat use along Bhutan's National Highways. Parameter estimates (logit scale) with 95% confidence intervals (LCI = lower confidence interval, UCI = upper confidence interval)

Model	Parameter	Estimate (Mean)	LCI	UCI
ψ ~ forest *(Forest cover effect)*	Intercept	**-1.5400**	-2.2208	-0.8593
	Forest cover	**0.0199**	0.0091	0.0308
ψ ~ ele + forest + river *(Full additive model)*	Intercept	**-0.7139**	-2.4827	1.0550
	Elevation	**-0.0003**	-0.0009	0.0003
	Forest cover	**0.0231**	0.0117	0.0345
	River distance	**-0.0096**	-0.0359	0.0167
ψ ~ 1 *(Null model)*	Intercept	**-0.3989**	-0.6496	-0.1482
ψ ~ river *(River proximity effect)*	Intercept	**-0.4050**	-2.0492	1.2391
	River distance	**0.0001**	-0.0241	0.0242
ψ ~ ele *(Elevation effect)*	Intercept	**-0.3576**	-0.8987	0.1835
	Elevation	**0.0001**	-0.0006	0.0005



Effect of Elevation on Occupancy

Effect of Distance to River on Occupancy

Effect of Forest Cover on Occupancy

Figure 3.3. Estimate of habitat use probability as a function of forest cover, elevation, and distance to the river. The green line indicates predicted covariate effects when all other covariates were held at their mean, and the dashed lines indicated 95% confidence intervals.

Building on the occupancy modeling results, the map (Figure 3.4) results visualize the spatial patterns of Golden Langur habitat use along Bhutan's road corridors. The lower map shows the elevation-based occupancy probability, which reveals only slight variation, confirming that elevation has a weak influence on habitat use. In contrast, the upper map highlights forest cover, which strongly predicts occupancy probability, with higher values concentrated in well-forested areas. Warmer colours (yellow) indicate greater occupancy likelihood, while cooler colours (purple) represent low probabilities. These spatial outputs reinforce that Golden Langur occupancy is primarily driven by forest availability, underscoring the importance of conserving intact forests.

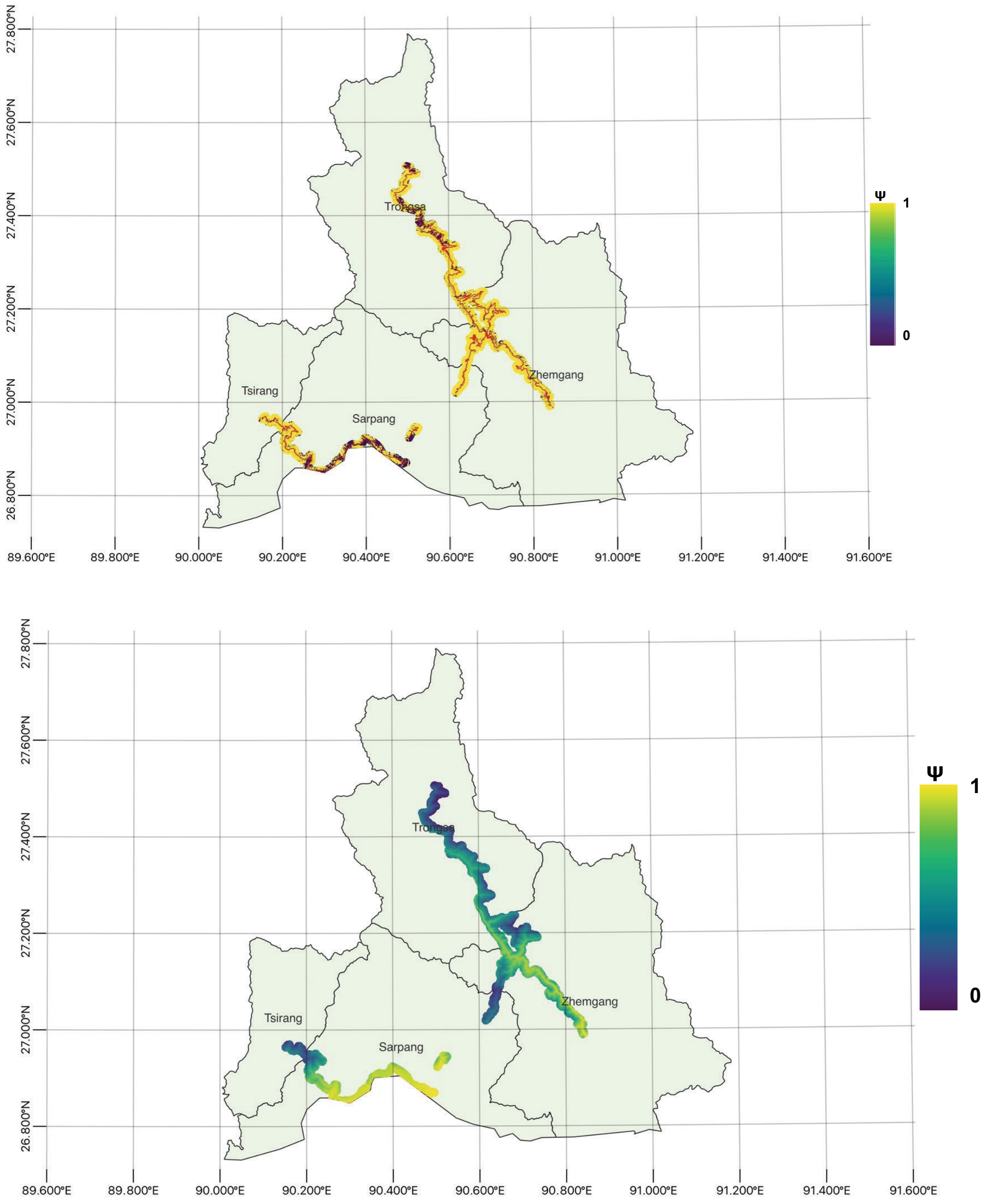


Figure 3.4. Spatial Variation in Golden Langur Occupancy Probability (ψ) in the Study Area

CHAPTER 4

DISCUSSION AND MANAGEMENT RECOMMENDATIONS

This study provides the first integrated analysis of Golden Langur (*Trachypithecus geei)* populations, occupancy patterns, and habitat use along Bhutan's national highway corridors. Roadkill is second most pertaining threats identified by past studies and the field observations of local rangers (Thinley et al., 2019). By combining population capture rates, demographic structure, site-specific abundance, and occupancy modeling, we reveal how forest cover, road infrastructure, and habitat fragmentation shape the species' distribution and persistence in a human-modified landscape.

4.1. Population Structure and Highway-specific Variations

The estimated population along surveyed highway corridors was approximately 1,908 individuals (95% CI: 1,617–2,256), with females comprising the majority (566), followed by juveniles (485), and fewer adult males (312). This female-biased sex ratio and the relatively high juvenile proportion are indicative of a demographically stable and actively reproducing population. Such a pattern aligns with the typical uni-male, multi-female social structure observed in Golden Langurs, where a single dominant male leads a harem-like group composed mainly of reproductive females and their dependent young (Rekha Chetry et al., 2017; Shil et al., 2020; Wangchuk, 2005). Healthy recruitment, reflected in the relatively large number of juveniles, suggests that despite localized threats, the overall reproductive output remains robust along many segments of Bhutan's road corridors.

However, population densities were not uniform across all corridors. For instance, Gelephu–Tsirang and Tingtibi–Pantang corridors supported the highest densities, which directly correlate with well-connected, mature forests characterized by continuous canopy cover and minimal anthropogenic disturbance. These areas act as ecological extensions of core habitats within Jigme Singye Wangchuck National Park (JSWNP) and Royal Manas National Park (RMNP), thereby benefiting from greater habitat integrity and resource availability. The groups in these zones also tend to exhibit larger group sizes (up to 12–15 individuals) and more balanced age classes, comparable to findings from protected populations in RMNP and Assam (Lhendup et al., 2018).

In contrast, Gelephu–Tsachhu and Tingtibi–Zhemgang–Wangdigang corridors harbored smaller populations with reduced group sizes, likely a result of habitat fragmentation, edge effects, and higher anthropogenic disturbance. Similar site-specific declines have been reported in Assam, India, where forest fragmentation caused by jhum cultivation and logging led to isolated and declining Golden Langur groups, some of which collapsed due to reduced reproductive success (Choudhury, 2008; Srivastava et al., 2001).

Another important observation relates to spatial demographic variability across highway networks. Groups in high-quality forests tend to maintain a natural sex ratio with stable male replacement dynamics, while those in fragmented habitats sometimes show skewed age-sex compositions, potentially reflecting the loss of adult males due to increased mortality risks, such as roadkill or electrocution (Das et al., 2008). This demographic imbalance, if persistent, can impair long-term social stability and breeding patterns.

The female-biased structure seen in most corridors may also reflect the dispersal behaviour of subadult males, which typically leave their natal groups upon reaching sexual maturity to establish new territories (R. Chetry et al., 2017). In highly fragmented areas, such dispersal opportunities may be limited, leading to a buildup of all-male or bachelor groups or even increased infanticide risk during unstable male takeovers (Wangchuk, 2005). Such behavioural consequences of fragmentation have been documented in hybridizing populations of Golden and Capped Langurs along the Indo-Bhutan border (Choudhury, 2008).

Highway-specific population variation also mirrors the gradient of human influence. Corridors closer to protected areas exhibit higher occupancy and group densities, whereas those passing through unprotected forests show lower population connectivity and reduced density. This underscores the importance of landscape context—highway corridors that function as ecological linkages between protected areas can sustain viable subpopulations, whereas those that are ecologically isolated may act as population sinks.

The patterns observed here also resonate with biogeographic constraints described by Wangchuk et al. (2008), where river systems like the Mangdechhu and Sunkosh historically shaped population structure by acting as natural barriers. In the modern context, roads, powerlines, and agricultural clearings play an equivalent role in fragmenting populations. Over time, such artificial barriers may exacerbate genetic isolation, a concern that has been highlighted in future land-use change projections for Golden Langur habitats (Chatterjee et al., 2022).

In the nutshell, while the overall population along Bhutan's highways remains stable with active reproduction, site-specific demographic patterns clearly reflect the influence of forest quality, canopy connectivity, and human disturbance intensity. The higher densities and healthier social structures in well-connected forest corridors emphasize the critical role of habitat integrity in maintaining viable populations. Conversely, the lower densities, smaller groups, and potential demographic imbalances in fragmented corridors signal early warning signs of habitat degradation that, if left unaddressed, could lead to long-term declines.

4.2. Occupancy Patterns and Habitat Drivers

Occupancy modeling revealed that forest cover is the primary determinant of Golden Langur habitat use along Bhutan's highway corridors. The forest-only model ($\psi \sim$ forest) was the most parsimonious, carrying the highest AIC weight, while elevation and river proximity contributed negligibly. This indicates that Golden Langurs' distribution is strongly tied to forest availability rather than topographic or hydrological gradients. Such findings are consistent with studies in Assam and Bhutan, where canopy continuity has been identified as the key habitat feature sustaining Golden Langur populations (Srivastava et al., 2001; Thinley et al., 2019).

The positive and significant effect of forest cover on occupancy ($\beta \approx 0.020$; 95% CI: 0.009–0.031) underscores the species' reliance on mature, multi-layered forests. These habitats provide safe arboreal pathways, seasonal food resources, and protection from predators. In contrast, open or degraded forests increase exposure to anthropogenic threats and limit movement between resource patches. Elevation and river proximity, though historically important in shaping the species' biogeographic range (Wangchuk et al., 2008), appear less relevant at the local scale of this study, where surveyed highways already lie within the species' elevation range (150–2,000 m).

The spatial occupancy maps highlight high-probability zones in forest-rich segments, such as the Tingtibi–Pantang and Gelephu–Tsirang corridors, whereas degraded stretches like Gelephu–Tsachhu showed lower occupancy values. This spatial heterogeneity mirrors the fragmentation gradient along highways. In India, similar occupancy declines were observed in fragmented habitat mosaics, leading to isolated groups with reduced survival and recruitment (Choudhury, 2008). The

Bhutanese results reinforce the conclusion that forest integrity is the most critical predictor of occupancy, even in landscapes with relatively lower human disturbance compared to Assam.

Golden Langurs are highly arboreal, with limited tolerance for ground movement. Thus, any loss of canopy connectivity due to roads, agricultural expansion, or logging directly translates into reduced habitat usability. This canopy-dependence also explains why even small-scale fragmentation can have disproportionate effects on occupancy. These findings corroborate Chatterjee et al. (2022), who projected significant future habitat loss and fragmentation outside protected areas due to planned land-use changes. Therefore, maintaining canopy connectivity is essential for sustaining occupancy along both protected and unprotected corridors.

4.3. Threats and Anthropogenic Pressures

Occupancy patterns along highways also reflect underlying anthropogenic threats. Segments with low forest cover coincide with areas of higher road density, powerlines, and human settlements. These features introduce a suite of threats identified in the Golden Langur Conservation Strategy and Action Plan for Bhutan (July 2025 – June 2035), including habitat fragmentation, roadkills, electrocution, hybridization with capped langurs, and stray dog predation (NCD, 2025).

Habitat fragmentation from road widening and hydropower projects reduces forest connectivity, creating isolated forest patches. This not only lowers occupancy but also disrupts dispersal pathways for subadult males, which could lead to demographic imbalances and increased inbreeding risk over time. Roads also increase mortality through collisions, as documented in Assam, where langurs were killed by vehicles in fragmented roadside forests (Das et al., 2006). Similarly, electrocution from uninsulated powerlines is an emerging threat in Bhutan, with several incidents reported near settlements bordering highway corridors (Thinley et al., 2019).

Another concern is hybridization with capped langurs (*Trachypithecus pileatus*), which has been observed along the Indo-Bhutan border where fragmented habitats force the two species into closer contact (Choudhury, 2008). While not yet prevalent along the surveyed Bhutanese corridors, increasing fragmentation could heighten this risk. Hybridization undermines species integrity and could have long-term genetic consequences.

Stray dog predation and illegal pet trade, though currently low-level threats, may escalate with expanding settlements. In Assam, removal of infants for the pet trade has contributed to group instability and lowered recruitment (Horwich et al., 2013). These experiences underscore the importance of proactive management to prevent similar impacts in Bhutan.

4.4. Implications for Connectivity and Long-term Viability

The spatial variation in occupancy and population density underscores the importance of landscape connectivity for Golden Langur persistence. Although Bhutan retains extensive protected areas such as RMNP, JSWNP, and PWS, only about one-third of the species' potential habitat lies within these zones (Thinley et al., 2019). The remaining habitat, much of it along highways, acts as ecological corridors linking core populations. If these corridors become too fragmented, subpopulations may become isolated, reducing gene flow and increasing local extinction risk.

Wangchuk et al. (2008) highlighted that historical river barriers shaped Golden Langur phylogeography, leading to naturally separated populations (Wangchuk et al., 2008). Modern anthropogenic barriers, such as highways, settlements, and agricultural fields, now replicate this isolating effect, potentially accelerating genetic drift in smaller groups. Chatterjee et al. (2022) further warn that future land-use change outside protected areas could exacerbate fragmentation, leading to irreversible habitat loss.

Maintaining occupancy along highway corridors is therefore crucial for ensuring metapopulation connectivity. Without intervention, degraded corridors like Gelephu–Tsachhu and Tingtibi–Zhemgang could act as population sinks. Conversely, restoring canopy connectivity in these zones could stabilize group densities and sustain dispersal between major population strongholds.

4.5. Management Recommendations

Based on these findings and aligned with the Golden Langur Conservation Strategy and Action Plan for Bhutan 2025–2035 (NCD, 2025), the following measures are recommended:

1. ***Habitat Protection and Restoration***
   Restore degraded highway forest patches with native canopy-forming species critical for Golden Langur diet (Wangchuk, 2005). Expand buffer zones around high-occupancy corridors linking JSWNP, RMNP, and PWS to reduce edge effects and prevent settlement expansion.

2. ***Maintain and Enhance Connectivity***
   Manage ecological corridors connecting highway forests to adjacent protected areas. Install canopy bridges and arboreal crossings in roadkill hotspots to facilitate safe movement and reduce vehicle collisions.
3. ***Mitigate Infrastructure-related Threats***
   Insulate high-voltage powerlines and modify transformers in langur habitats to prevent electrocution (Thinley et al., 2019). Implement road signage, speed breakers, and awareness campaigns along critical highway segments to minimize roadkills.
4. ***Community Engagement and Stewardship***
   Involve local communities in habitat restoration, corridor monitoring, and stray dog management. Support community forestry and eco-tourism initiatives to reduce reliance on roadside forests and enhance conservation awareness (Horwich et al., 2013).
5. ***Policy Integration and Enforcement***
   Integrate occupancy maps into Environmental Impact Assessments (EIAs) for highways and hydropower projects. Strengthen enforcement against illegal pet trade and monitor potential hybrid zones near the Indo-Bhutan border (Choudhury, 2008).
6. ***Monitoring and Research***
   Establish long-term occupancy monitoring plots to detect population and habitat changes over time such as inclusion of golden langur Biodviersity Monitoring Grid. Conduct genetic studies to assess gene flow between highway populations and core protected areas, identifying isolation risks. Expand site-specific surveys in under-sampled areas identified by predictive models (Chatterjee et al., 2022).

4.5. Conclusion

This study advances our understanding of Golden Langur ecology in Bhutan by integrating population demographics, highway-specific densities, and occupancy patterns with key habitat attributes. The findings underscore the role of highway corridors as both essential ecological linkages and potential threats to long-term population viability. While the species demonstrates stable reproduction and healthy social structures in forest-rich corridors, ongoing infrastructure development poses emerging risks to connectivity and genetic exchange.

The study highlights the value of combining spatial modeling with demographic monitoring to inform conservation planning at multiple scales. It also provides a practical framework for prioritizing corridor restoration and targeted mitigation along development zones. Most importantly, it aligns directly with the Golden Langur Conservation Strategy (2025–2035), offering evidence-based guidance for future management. Sustaining the species' viability will depend on proactive, landscape-level interventions that integrate habitat restoration, infrastructure planning, and community stewardship to balance conservation with Bhutan's development priorities.

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ANNEXURE I: Golden Langur Threat Survey Questionnaire (phone-based form was developed on epicollect app)

1. Transect details

Name of Division:……………..

Name of Range/Guard Post:…………..

Name of highway:……………………

Distance travelled:…………………..

2. Animal capture history

Time & date	**GPS coordinates**	**Number of individuals in a group**	**Host tree species**	**Transect**	**Evidence of human feeding, type of food**	**General comments**
		e.g., Juvenile: 2, Male: 5, female: 6		Road/Transmission line		Same group as previous

** The survey team will traverse 3 times along the transect (6-8 am) and 4-6 Pm)

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