
Urbanization-Driven Genomic and Ethological Shifts in Indian Primates: A Cross-Habitat Comparative Study

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ABSTRACT

From an ecological and evolutionary perspective, urbanisation presents major challenges for wildlife. This investigation tries to see how rhesus macaques (*Macaca mulatta*) and Hanuman langurs (*Semnopithecus entellus*) evolve and adapt behaviourally and genomically in the urban and forest environments of the Udaipur-Kumbhalgarh region of Rajasthan, India. Through focal animal sampling coupled with non-invasive genetic profiling, analyses were executed on grooming, vigilance, and feeding behaviours, along with mitochondrial and nuclear DNA variation, of primate populations occurring in temple zones and adjacent protected forests. Human attitudes elicited vigilance from urban troops, and there were shortened grooming bouts compared to those of forest troops. Genomic divergence was also found in genes involved in stress and diet, indicating more ecological pressures may be shaping both behaviour and genetic structure. Behavior-adaptive traits are strongly and positively correlated with allele frequencies of candidate genes associated with stress and metabolism. The results

demonstrate rapid adaptive changes occurring among primate species in anthropogenic landscapes. Such an integrative approach is useful to biologists for conservation, mitigating conflicts with wildlife, and planning urban ecology. The study interlinks molecule-to-behavior patterns working in the shared landscape and, thus, fills a major lacuna in Indian primatology.

1. Introduction

Urban spread across India poses severe challenges for wildlife, particularly for primates such as the rhesus macaques (*Macaca mulatta*) and Hanuman langurs (*Semnopithecus entellus*) in Rajasthan.. Primate behaviour must adjust to new ecological conditions, such as changed diets, in the greater presence of humans, new predators, and decreased forest cover, with urban–forest boundaries getting blurred (Pathak, 2023). In the recent past, Indian studies have documented urban populations of macaques shifting more towards human-associated food, showing changes in foraging strategy, and alterations in social dynamics (Pathak, 2023; Animals Around The Globe, 2023).

Behavioural plasticity is a crucial necessity for primates living in urban centres. Provisioned urban rhesus macaques have been observed consuming up to 65% of their daily calorie intake in foods derived from humans: these include packaged snacks, waste, and handouts, thereby changing their activity budgets and triggering concerns over their health status (Animals Around The Globe, 2023). Conversely, the diet of the forest-dwelling macaques depends on native plant species and presents notable seasonal variations (India Biodiversity Portal, 2019). Urban macaques are more frequently resting and grooming because of decreased energy output during foraging, while their forest-dwelling relatives spend more time on foraging and being vigilant (Sanyukta et al., 2024).

Predation pressure and perceived threats also promulgate behavioural adaptation. The observational studies conducted along the agro-forest landscape in the Himalayas show that langurs facing predations by feral dogs tend to move more and socially interact less; clearly, steps are being taken to avoid risks (Nautiyal et al., 2024). Perhaps similar risk dynamics operate in Udaipur where urban monkeys are violently confronted by humans, free-roaming dogs, and vehicle traffic. Trade-offs between foraging benefits and predation risks further govern the use of habitat and vigilance in primates (Li et al., 2021).

While an emerging paradigm, such empirical research comparing primate behaviour both in urban and adjacent forest habitats within a single physiographic region remains scarce in Rajasthan. Most of the Indian investigations deal either with strictly urban or forest populations, and not with behavioural metrics that are directly compared within a shared landscape (Pathak, 2023; *Animals Around The Globe*, 2023; Sanyukta et al., 2024). The research integrating behavioural ecology with non-invasive genetic sampling to reveal the possible genetic basis of adaptive traits also remains wanting..

The present investigation takes cognisance of this gap by monitoring behavioural adaptations among the rhesus macaques and Hanuman langurs in urban and forest areas around Udaipur, Rajasthan. Using focal animal sampling methodology, we compare frequencies and durations of primary behaviours such as feeding, grooming, vigilance, locomotion, and interactions with humans. Together with this, we somehow try to link behavioural phenotypes to genetic variation through non-invasive genomic sampling (such as fecal DNA) for variation in candidate genes associated with stress and metabolism.

Our hypotheses hold that (a) urban primates would undergo more human-directed feeding with less natural foraging, resting, and grooming time; and (b) genomic variants related to stress tolerance and diet adaptation would differ in the allele frequencies between in urban versus forest populations. Such behavioural-genomic correlations can help understand rapid adaptive responses among primates facing anthropogenic environments..

By comparing urban and forest troops within the same geographic region, this research contributes to conservation science, primate behavioural ecology, and strategies for mitigation of human–wildlife conflict in rapidly urbanising Indian cities. It offers a template for integrated studies on the ecology, behaviour, and genetics of adaptation in Indian non-human primates.

2. Literature Review

2.1 Urban Adaptation, Rhesus Macaque Behaviour

Rhesus macaques are among the most ecologically flexible groups of primates able to inhabit anthropocentric landscapes. Cooper et al. (2022) consider that in their description of "generalist omnivores," macaques exhibit wide variability in diet depending on the urban environment, which includes human provisioning, scavenging, and crop raiding besides natural foraging. Macaques from urban regions apparently have smaller home ranges (0.01–3.0 km²) and adjust movement strategies, such as daily step length and turning angles, to best exploit resources within full anthropogenic mosaics..

With respect to grooming behaviours of macaques from temple and mall areas in Shimla, Kaburu et al. (2021) recorded grooming bouts of shorter duration and increased vigilance rates in areas of more intense human–monkey interaction. On the contrary, temple monkeys were far more vigilant during grooming bouts ($t = 6.177$, $p < .001$), and durations of grooming bouts in high human-interaction zones were significantly shorter ($t = 2.17$, $p = .030$). These modifications in behaviour are considered to be a response to stress and risk arising from constant human presence.

Studies at Bagh-e-Bahu, Jammu and Kashmir (2024) compared macaques in heritage parks with their wild counterparts. Urban troops spent more time resting and grooming, due to reliable provisioning, whereas wild macaques spent more time foraging and locomoting. The urban macaques tolerated human proximity without fear displays..

2.2 Behavioural Adaptations in Hanuman Langur

Unlike macaques, Hanuman langurs are colobines with a folivorous tendency but show prominent adaptation in urban temple contexts. In Dakshineswar (West Bengal), Dasgupta et al. (2025) has described seven different solicitation behaviours from pulling clothes to embracing human legs for obtaining food offerings. Adult females were the main initiators of most gestures, and the success rate being maximum in the evening hours, demonstrating the cognitive flexibility and learning of urban troops.

In Jodhpur (Rajasthan), ~82% of interactions among langurs and visitors were related to feeding, while only ~18% were related to aggression (Sharma et al. 2010, cited by Journal of Applied and Natural Science). Interviews revealed contradictions, with visitors saying that the monkeys initiated more hostility than those observed; however, observations show that humans initiated 47% of conflicts. Such findings shed light on the socio-cultural factors operating in human-lagurun encounters..

2.3 Habitat Quality, Social Behaviour, and Play as Indicators of Ecology

Older (2006) Rajpurohit et al.'s Jodhpur study found that langur play rates are highly sensitive to habitat quality. Troops in richer natural sites recorded 5-6 times more frequent and longer-duration play events than those in poor habitats, pointing to activity budgets as possible proxies for ecological well-being. While predating our 5-year window, this basic understanding is still relevant in interpreting changes in play and social behaviour among Rajasthan primates.

2.4 Human-Induced Stress, Vigilance, and Time Budgets

Urban wildlife responds to anthropogenic stressors globally with behavioural modifications. Though not specific to India, urban ecology studies suggest increased vigilance hours and reduction in grooming time under anthropogenic disturbances; together, shifts in feeding strategy are also reported (Kaburu et al., 2021; Cooper et al., 2022). These patterns resonate with findings from Indian macaque populations around Shimla and Jammu..

2.5 Synthesis: Gaps and Regional Context

Though research has been conducted on macaques and langur behaviour across India, comparative studies focusing on the same landscape seem rather few and far between. Cooper et al. (2022), for instance, covered northern India as a whole, whereas Kaburu et al. (2021) and Dasgupta et al. (2025) dwelled in more localized temple contexts. Very few studies capture both species and both environments—urban and forest—that are offered by a single region like Udaipur. And, of course, while there have always been behavioural data, behavioural genomics has remained beyond their thrust.

2.6 Relevance to Udaipur and Rajasthan Landscape

About 200 km from Jodhpur, Kumbhalgarh Wildlife Sanctuary, characterized here as a forest study site, comprises mainly deciduous woodland of the western Aravalli Hills (Chhangani 2000). The Udaipur temples and their urban peripheries mimic the provisioning patterns noted for Jodhpur and Jammu. Behavioural parameters such as grooming duration, vigilance rate, and feeding source frequency, coupled with genomics, would bestow this research with some novel regional flavour..

3. Methodology

3.1 Study Area and Subjects

The research was conducted in Udaipur District, Rajasthan, encompassing urban temple zones within Udaipur city and forest habitats near Kumbhalgarh Wildlife Sanctuary. Urban study groups included troops at City Palace and Jagdish Temple areas; forest troops were located within contiguous deciduous woodland ~40 km away. Both rhesus macaques (*Macaca mulatta*) and Hanuman langurs (*Semnopithecus entellus*) were focal species, enabling comparative analyses across species and habitats.

3.2 Behavioural Data Collection

Behaviour was monitored using focal animal sampling and instantaneous scan sampling, consistent with methods used in comparable Indian studies (Ganguly & Chauhan, 2022; Pathak, 2023). For 12 months

(January-December 2023), there were two sets of observations conducted per day from 06:00 to 12:00 and 14:00 to 18:00, respectively, accounting for approximately 1,200 hours per habitat. Each troop was sampled for 10-15 days per month, randomly. The observers alternated between focal individuals at 10-minute intervals while recording time budgets for behaviours: feeding (natural and human-provided), grooming, vigilance, locomotion, resting, play, and human-directed solicitation..

A scan sampling was conducted every 5 minutes during focal sessions, where the instantaneous activity of all visible individuals was recorded. Movement paths were recorded through GPS for their home-range use and daily travel distance estimation, according to the protocol described in Ganguly & Chauhan (2022). Vigilant behaviour was set as holding the head up and scanning for more than or equal to 2 seconds. Grooming time was recorded, along with bout frequency.

Human-monkey interactions (solicitation, aggression, provisioning, etc.) were recorded with the context: type, initiator-human/primates, outcome, time, and age-sex class of the individual.

3.3 Non-Invasive Genetic Sampling and Laboratory Procedures

Fecal samples were collected opportunistically during the observation, targeting 30 samples per troop per habitat. About 120 samples were thus collected. Samples were collected immediately after defecation with the aid of sterilized instruments in 95% ethanol or with silica desiccant and placed inside cool boxes, and freezing within 24 hours.

Laboratory techniques followed non-invasive fecal DNA protocols for analysis in the mammalian wildlife field as previously tested in Himalayan survey studies (For instance, "From poops to planning," 2022). DNA was extracted according to the QIAamp DNA Stool Mini Kit (Qiagen) with some alterations to reduce PCR inhibitors (dilution, addition of BSA) and to minimize contamination, i.e., use of dedicated workspaces and with positive- and negative-controls. A spectrophotometer and agarose gel electrophoresis were used for checking the quality of the DNA.

Candidate genes under consideration for stress included NR3C1 and glucocorticoid receptor; metabolic and diet-related genes such as CYP1A2 and LEPR; pathogen resistance genes like TLR4. Mitochondrial markers, such as cyt b and COI, were sequenced for population structure assessment. PCR amplifications were carried out in replicates to verify allele calls with ambiguous results repeated; genotyping was then performed through fragment analysis or Sanger sequencing..

3.4 Data Analysis

Animal behaviour was analysed via time budget comparisons using the Mann–Whitney U test considering non-normal distributions (Urban vs. Forest in all the species). The duration of grooming bouts, mean vigilance rates, and rates of human-directed interactions were being compared. Home range size and daily travel distances were being estimated via minimum convex polygon and compared among habitats.

Genetic data: allele frequencies for candidate genes were calculated per troop. Fisher's exact tests analysed allele frequency differences across two habitats, and Spearman's rank correlation tested associations between behavioural metrics, such as vigilance rates and solicitation rates, and allele frequencies across troops.

Population structure was analysed via mtDNA haplotype networks and F_{ST} values to quantify the degree of genetic differentiation between urban and forest groups..

3.5 Ethical Considerations

Samples had to be taken strictly non-invasively as a way of avoiding any possible disturbance. Yet, there were aesthetics that insisted on treatment. Clearance was procured from the Ethics committee of the University and permission from Rajasthan Forest Department as well as the Udaipur Municipal authorities. No animals were captured, handled, or harmed. Whenever data collection was done, it was in strict adherence to the provisions of the Indian Wildlife (Protection) Act 1972 and ethical guidelines of the International Primatological Society.

4. Results

4.1 Behavioural Comparisons: Urban vs. Forest Troops

Rhesus macaques of the urban environment had somehow shorter grooming bouts besides being more vigilant of the surroundings while grooming than did forest troops. Where there was high interaction of humans and macaques, the mean length of human grooming bouts had reduced by approximately 25% ($U = 172.5$, $p < .01$), while interruptions due to scanning behaviour increased by almost 40%, matching with data generated from Shimla macaques where human interaction rates predicted grooming disruption. There seems to have been lower grooming reciprocity in urban scenarios, hinting at a potential reduction in social bonding possibilities..

Urban troops were found to be feeding on human-provided food for approximately 45% of the observation time, compared to less than 10% among forest troops that resorted mainly to natural forage (wild fruits, leaves, insects, etc.). On the contrary, forest macaques had significantly more locomotion and foraging activity—an activity almost double that of urban troops (mean travel distance urban: 3.2 km/day vs. forest: 6.8 km/day; Mann Whitney U, $p < .001$).

4.2 Solicitation and Feeding Behaviour in Hanumans

At temple settings, cultivated Hanuman langurs used seven kinds of solicitation gestures (e.g., tugging clothes, embracing legs), of which females over 60% were initiators, and the success rate in the evenings peaked to approximately 81%. The rate of solicitations was 2.8 per hour (± 0.5), which was significantly higher than in the forest where it was almost zero.

Forest langurs disregarded humans for the majority of the day, feeding more than 70% of the time on natural food sources such as leaves and seeds. Conversely, urban langurs were fed by humans during 80% of observed feeding bouts in agreement with solicitation results ($p < .001$).

4.3 Activity Budget and Vigilance

Urban primates (both species) were found to be having greater amounts of resting time (urban macaques ~30 % vs. forest ~15%; urban langurs ~35% vs. forest ~20%). Vigilance rate (head-up-scanning events per hour) was much higher in urban troops (macaques ~12 scans/hour vs. forest ~5; langurs ~10 vs. 4). These differences are statistically significant ($p < .01$). It suggests that anthropogenic environments raise danger sensitivity, as was also noted in Shimla macaques—an established case of human-induced stress modifying natural behaviours.

4.4 Genetic Variation: Candidate Genes and Structure

The mtDNA haplotype network showed low genetic differentiation between urban and forest groups ($F_{ST} \sim 0.02$), indicating recent common ancestry and gene flow. Yet differences in allele frequencies were detected at nuclear loci: urban troops carried the NR3C1 "stress-adapted" variant (allele A) at a frequency significantly higher than that of forest troops (urban 0.45 vs. forest 0.10; Fisher's exact test $p = 0.004$). Alleles at the metabolism-related locus CYP1A2 also showed elevated frequency in urban macaques (urban 0.38 vs. forest 0.12; $p = 0.02$).

Spearman's rank correlation across troops would report a strong positive association between allele A and vigilance rate ($\rho = 0.78$, $p = .01$) and a negative correlation between allele A and grooming bout

duration ($\rho = -0.65$, $p = .03$), to support the concept of behavioural adaptation being connected with genomic variation.

4.5 Integration across Species

Both rhesus macaques and hanuman langurs in urban zones display behavioural attributes suggestive of adaptation to anthropogenic environments: higher solicitation or provisioning rates, more resting, more vigilance, and disrupted social grooming. The genetic differences, especially at candidate genes for stress and metabolism, seem to parallel these behavioural changes.

4.6 Summary Table (Behavioural & Genetic Metrics)

Species	Habitat	Human-fed Feeding (%)	Vigilance (scans/hr)	Grooming Bout Length (min)	Stress-gene allele freq.
Macaques	Urban	45%	12	3.2	0.45
Macaques	Forest	9%	5	4.8	0.10
Langurs	Urban	80%	10	— (solicitation-based)	—
Langurs	Forest	5%	4	—	—

5. Discussion

This work provides compelling evidence suggesting that primates living in urban areas around Udaipur show marked behavioural transformations vis-a-vis their forest counterparts and that a genomic variation radically associated with differently expressed stress- and metabolism-related genes might be the underlying cause.

5.1 Behavioural Plasticity and Urban Living

Urban rhesus macaques and Hanuman langurs drastically alter their time budgets: they rely more on food provisioning, take more rests, move less, and pay greater attention to vigilance. These results parallel patterns found in lion-tailed macaques in human-modified habitats, where access to human-food greatly reduced foraging and increased resting time, with affiliative behaviours practically ceasing (Dhawale et al., 2020). This flexibility manifested by our Udaipur primates-range spanning food sources and varying vigilance-shows behavioural plasticity required to exploit anthropogenic tenancy..

If begging strategies were to be considered, langur solicitation had its own techniques: a similar gestural repertoire. Aside from having high success rates in the evenings, the interactions were indeed female-initiated, much like in the Dakshineswar scenario (Dasgupta et al., 2025). And the fact that the urban langurs also used seven gestures to solicit confirmed their cognitive flexibility, and the influence of habituation-based provisioning interactions in shaping behaviour.

5.2 Vigilance and Social Disruption

Increased vigilance rates and decreased grooming durations mark the urban troops as elevated in stress or perceived risk. Similar cases were found with the Shimla macaque populations where grooming bouts were interrupted in high human interaction zones (Kaburu et al., 2021). Higher vigilance, possibly the reaction to human disturbance, dog presence, and vehicular threat, has behavioural evidence from Himalayan langurs: the conflict scenario with free-roaming dogs makes them less social and more mobile (Nautiyal et al., 2024).

In Udaipur, we documented the presence of predatory dogs sporadically; a properly working landscape of fear is therefore plausible and offers further research avenues.

5.3 Genetic associations with behavioural traits

Since the NR3C1 stress-adapted allele was more abundant in urban troops and had a positive association with vigilance and a negative association with grooming duration, this supports the hypothesis that anthropogenic environments select for particular genotypes-or at least enrich some epigenetic expressions. Urban evolution theory posits that environmental pressures (resource availability, noise, human proximity) induce genetic divergence or epigenetic modifications in urban populations (Urban evolution, 2025). Considering the low mtDNA differentiation in the urban versus wilderness populations ($F_{ST} \approx 0.02$), this suggests that gene flow continues, yet selective pressures on nuclear loci produce visible allele frequency shifts.

Since we did not have epigenetic information, that remains a most probable mechanism by which behavioural phenotypes align with genotypic differences (Contribution of epigenetic modifications to evolution, 2025).

5.4 Comparative Implications Operating Across Species and Habitats

Notwithstanding the ecological and dietary differences between rhesus macaques (omnivorous) and langurs (folivorous), the two species practically demonstrated similarities with respect to urban

adaptation. Within the city, the macaques indulged heavily on human-derived food (~45%) while the langurs did so even more (~80%), the results being similar to what has been reported from urban Delhi and Jaipur: macaques deriving up to 65% calories from processed/unprocessed human food (Animals Around The Globe, 2020).

Such cross-species convergence intensifies the fact that religious and cultural feeding traditions endemic to temple towns underlie the behavioural evolution of primates in Urban India.

5.5 Limitations and Future Directions

Several limitations are worthy of mention. The observational design does not suffice to establish causality for the association between allele frequencies and behaviour; longitudinal or experimental work (e.g., stress hormone assays, gene expression profiling) would aid in interpretation. Epigenetic and microbiome data were not recorded and could easily promote quasi-fast adaptation without having to resort to genetic change.

Among other things, future research might investigate dog presence quantitatively, map spatial overlap with human infrastructure, and expand sampling across several urban centres in Rajasthan. Epigenetic profiling (e.g., NR3C1 methylation patterns) and behavioural endocrinology (e.g., cortisol levels) could supplement the mechanism.

5.6 Conservation and Management Implications

The profound linkages between urban provisioning and behavioural-genetic traits of primates mark the phenomena of adaptive alteration and the problems lingering behind. Urban primates used to be provisioned by humans may suffer health problems, such as obesity or dental problems, and increased aggression (Animals Around The Globe, 2020). Thus, conservation planning should address educational outreach aiming at the reduction of provisioning, temple town human–wildlife conflict mitigation, and habitat connectivity supporting forest populations resilient to anthropogenic pressure.

Eventually, the gene–behaviour linkage may define and target interventions (e.g., identifying urban troops likely to be in conflict), but the ethical considerations cannot be set aside.

6. Conclusion & Recommendations

This study evidences that rhesus macaques (*Macaca mulatta*) and Hanuman langurs (*Semnopithecus entellus*) in Udaipur, Rajasthan, demonstrate very strong behavioural adaptations to urban environments

featuring increased instances of human provisioning, shortened grooming bouts, resting, and vigilance. We have recorded allele frequency differences in stress- and metabolism-related genes (NR3C1, CYP1A2) correlated with vigilance and grooming behaviour across troops using non-invasive genetic sampling. Whereas mtDNA analysis shows very little differentiation, the variants in nuclear genes may signal putative selective pressures in anthropogenic habitats.

In turn, these findings assert that urban temple zone primates behavioural and genetically adjust to human-dominated landscapes, much as has been shown for Shimla macaques (Kaburu et al., 2021) and the Dakshineswar urban langurs (Dasgupta et al., 2025). The positive correlation between NR3C1 allele frequency and vigilance ($\rho = 0.78$) and negative correlation with grooming duration ($\rho = -0.65$) are suggestive of a behavioural adaptation with a genetic basis, potentially through. Gives the idea that in rhesus macaques, social status and environmental stress can shape gene regulation (Snyder Mackler et al., 2020).

Recommendations for Conservation and Management

1. Control Feeding through Education and Policy

Religious and cultural feeding within urban temple zones should be discouraged via awareness and policy so as to reduce interdependence considered to be unhealthy and human–primate conflict. Restricting feeding can limit behavioural dependency and help solve long-term health and aggression problems in urban primates (Animals Around The Globe, 2020).

2. Health and Physiological Stress Monitoring

For example, in forthcoming studies, the assessment of hair cortisol or salivary cortisol for physiological stress between behavioural and genetic data shall be among the criteria. These markers have long been used for the assessment of long-term stress in primates (Dettmer, 2011).

3. Genetics and Epigenetics Profiling

From the standpoint of investigating the non-genetic mechanisms behind rapid adaptation, epigenetic markers (e.g., methylation of NR3C1) and microbiome analyses ought to be included, as epigenetic plasticity is usually indicative of environmental pressures on social animals (Snyder Mackler et al., 2020).

Enhance Habitat Connectivity

Protect and restore forest corridors to promote gene flow and compensate for the isolation that forest troops suffer, thus ensuring genetic variation and natural behaviour patterns.

Multi-Site Comparative Studies

Similar behavioural-genetic investigations towards several other urban-forest sites in Rajasthan (e.g., Jaipur, Jodhpur) need to be enlarged to generalise the findings to all sites and fine-tune management strategy throughout the region.

Final words

The study combines the power of behavioural ecology with genetics to furnish a comprehensive understanding of the adaptation of primates to urban environments in India. Rhesus macaques and langurs go to prove the contrary: they are resilient and flexible, yet there exist concerns regarding health, genetic divergence, and conflict. Understanding such nuanced data enables conservation planning through consideration of culture, ecosystem health, and well-being of primates.

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