

Riverine riparian corridors as critical foraging and movement microhabitats for Asian Elephants (*Elephas maximus*) in fragmented landscapes of Northeast India

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Abstract

The Asian elephant (*Elephas maximus*) faces severe anthropogenic habitat fragmentation across South Asia, where terrestrial land-use conversions strictly preclude the gazettement of expansive continuous terrestrial protected reserves. In such human-dominated multi-use matrices, natural riparian river networks represent critical, topographically unconstrained microhabitats that simultaneously provide foraging resources, perennial water, and low-resistance movement pathways. We conducted an empirical investigation across 820 contiguous 1-km reach units along 11 major tributary networks of the Brahmaputra River in the North Bank Brahmaputra Landscape (NBBR) of Assam, Northeast India. A dual-detection survey protocol (combining standardized pedestrian sign searches with structured key-informant interviews across 500-m reach buffers) yielded an empirical detection probability of $p = 0.82$ and documented elephant presence across 429 reaches (naïve occupancy = 52.3%). Generalized Linear Mixed-effects Models (GLMM; marginal $R^2 = 0.67$, conditional $R^2 = 0.94$) with river basin as a random intercept revealed that elephant riverine site-use was strongly favored in upper foothill entry reaches ($\beta = +3.83 \pm 0.46$, $P < 0.001$; Odds Ratio [OR] = 46.19) and river channels with high discharge volume ($\beta = +0.47 \pm 0.19$, $P = 0.015$; OR = 1.60). Proximity to matrix land covers—specifically commercial tea plantation agroforests ($\beta = -2.17 \pm 0.28$, $P < 0.001$; OR = 0.11), alluvial grasslands ($\beta = -1.16 \pm 0.28$, $P < 0.001$; OR = 0.31), and protected forest reserves ($\beta = -1.43 \pm 0.48$, $P = 0.002$; OR = 0.24)—substantially elevated site-use odds, underscoring that tea estate shade canopies serve as vital diurnal stepping-stone refuges. Conversely, low-clearance transport infrastructure (< 4.5 m vertical underpass clearance) exerted severe negative deterrence ($\beta = +1.60 \pm 0.30$, $P < 0.001$; OR = 4.97), compressing channels and deflecting moving herds into agrarian settlements. Spatial projection of the parameterized model across 9,679 regional river segments in 30 drainage basins identified 5,674 functional corridor reaches (ROC AUC = 0.93; 5-fold cross-validation AUC = 0.875). Continuous corridors connecting $> 1,200$ km² of core foothill reserves were identified along the Jia-Bharali, Bargang, and Buroi rivers. We propose three actionable interventions: mandatory bridge underpass clearances (≥ 5.5 m vertical height, ≥ 30 m horizontal span), statutory gazettement of 1-km riparian buffers, and formal tea estate agroforestry partnerships to secure megaherbivore gene flow and promote sustainable human-elephant coexistence.

Keywords: Asian Elephant, Brahmaputra River Basin, generalized linear mixed-effects model, human-elephant conflict, landscape connectivity, linear infrastructure, riparian corridors

Introduction

Large terrestrial mammalian herbivores are exceptionally vulnerable to anthropogenic habitat loss and landscape fragmentation across South and Southeast Asia^[1]. Due to their high daily metabolic and hydrological demands, megaherbivores require vast contiguous tracts to maintain gene flow, sustain demographic stability, and track seasonal nutritional pulses^[2, 3]. The Asian elephant (*Elephas maximus*), listed as Endangered on the IUCN Red List^[4], is Asia's largest extant terrestrial mammal. An adult elephant requires up to 150 kg of vegetative biomass and over 100 L of water daily, dictating annual home ranges varying from 250 km² to over 2,600 km²^[1, 2]. Over recent decades, however, agricultural expansion, human settlements, and linear infrastructure have fragmented subtropical forests into isolated habitat patches embedded within dense human-dominated matrices^[1, 5].

In densely settled agrarian landscapes, creating extensive new statutory protected areas is socio-economically and politically unviable^[6]. Consequently, identifying and maintaining functional ecological connectivity through permeable matrix habitats represents the primary conservation mechanism to prevent meta-population

collapse and mitigate escalating human-elephant conflict (HEC)^[7, 8]. Fluvial networks and riparian zones represent exceptional natural conduits in human-modified landscapes^[9, 10]. Riparian corridors provide three fundamental ecological co-benefits: (1) permanent hydrological access and microclimatic thermal buffering during hot dry periods, (2) early-successional, flood-adapted alluvial graminoids (*Saccharum*, *Phragmites*, and *Typha* spp.) that regenerate rapidly after monsoon inundation, and (3) broad, low-gradient alluvial sandbars that serve as natural movement corridors through densely settled valleys^[3, 11].

Energetic movement models show that gravitational energetic expenditure is heavily minimized when heavy quadrupeds travel along flat alluvial riverbeds rather than traversing undulating terrain or navigating agricultural obstacles such as ditches and fences^[11, 12]. Despite this theoretical importance, quantitative empirical research investigating the interactive effects of fluvial geomorphology, surrounding matrix land use, and anthropogenic linear barriers on elephant microhabitat selection remains sparse^[13].

The North Bank Brahmaputra River (NBBR) landscape of Assam, Northeast India, represents a globally critical

stronghold, supporting approximately 20% of India's wild Asian elephant population [6]. Bordered by the forested Himalayan foothills of Bhutan and Arunachal Pradesh to the north and the Brahmaputra River to the south, the NBBR forms an intricate mosaic of core protected areas (Manas, Nameri, Sonai Rupai, and Kaziranga), commercial tea estates, and intensive paddy cultivation [14, 15]. Over the past three decades, dense forest cover in the landscape has declined by more than 13%, intensifying HEC and resulting in an annual average of 64 human deaths and 28 elephant fatalities between 2000 and 2023 [16]. Over 60% of the transitional matrix between foothill reserves and southern floodplains is under intensive human use.

Significantly, river channels in this landscape are increasingly crossed by road and railway bridges with low vertical underpass clearances and steep embankments [17, 18]. These engineering structures can constrict alluvial corridors, deflecting elephant herds into human habitations and escalating conflict. Here, we systematically sampled 820 contiguous 1-km reach units across 11 major river networks in the NBBR to: (1) quantify the effects of fluvial geomorphology, matrix land cover, and infrastructure proximity on elephant site-use; (2) evaluate the functional role of commercial tea plantations as diurnal stepping-stone refuges; and (3) generate a validated regional corridor model to guide targeted infrastructure retrofitting and riparian conservation policies.

Materials and methods

Study area and fluvial networks

The study was conducted across the North Bank Brahmaputra River (NBBR) landscape in Assam, Northeast India (5,150 km²; 26°15'N to 27°00'N, 91°45'E to 93°45'E). The region experiences a tropical monsoon climate with annual rainfall between 2,000 mm and 3,500 mm [16]. Topographically, the landscape transitions from the bhabar-terai alluvial fan tract along the Himalayan foothills (150–450 m a.s.l.) to the gently sloping alluvial floodplains of the Brahmaputra River (45–100 m a.s.l.).

Eleven major snow- and rain-fed tributary networks draining southwards into the Brahmaputra were systematically delineated: Aie, Pagladia, Bornadi, Dhansiri, Pasnoi, Belsiri, Jia-Gabharu, Jia-Bharali, Bargang, Buroi, and Subansiri. Based on HydroSHEDS HydroRIVERS classifications [19] and Sentinel-2 satellite imagery, these river systems were stratified into two hydrological groups: (1) Order 5–7 Large River Systems (Aie, Jia-Bharali, and Subansiri), defined by long-term average (LTA) discharge > 10 m³/s, active channel bed width (CBW) > 1,000 m, and deep-water channels (DWC) > 3 m; and (2) Order 3–5 Medium-to-Small River Systems (Pagladia, Bornadi, Dhansiri, Pasnoi, Belsiri, Jia-Gabharu, Bargang, and Buroi), characterized by LTA discharge between 0.01 and 10 m³/s, CBW < 1,000 m, and seasonally shallow water depths (DWC < 3 m during low-flow periods).

Sampling design and site-use assessment

Using Sentinel-2 satellite imagery (10-m resolution) and GIS hydrographic vectors, the active channels of all 11 river networks were partitioned into contiguous 1-km reach units, yielding 820 sampled reach segments. Field surveys were conducted across all 820 segments between December 2023

and October 2024, spanning dry-winter, pre-monsoon, and post-monsoon seasons. Elephant site-use (presence/absence) within each reach unit was determined using a standardized dual-detection protocol:

(1) **Standardized Physical Sign Surveys:** Two-person trained wildlife teams walked pedestrian sign transects along active sandbars and vegetated riverbanks (minimum 200 m search path per reach). Surveyors recorded fresh and weathered dung piles, tracks, mud-rubbing marks on riparian trees, and feeding signs on riparian tall grasses (*Saccharum ravennae*, *S. spontaneum*, *Phragmites karka*, *Typha elephantina*) [3]. (2) **Structured Key-Informant Surveys:** Structured interviews were conducted with local residents, forest personnel, and tea estate guards living or working within 500 m of each segment [20]. Informants were queried on documented elephant presence, crossing frequencies, and herd passage over the preceding 12 months using pictorial verification.

Replicated spatial-revisit occupancy modeling across a 20% random subsample (n = 164 reaches surveyed three times independently) yielded an estimated detection probability of $p = 0.82$ (cumulative $P^* > 0.96$). Because the combined protocol ensured high detection fidelity, binary presence/absence responses were treated as robust site-use indicators in logistic mixed-effects regression, minimizing false-negative bias [21].

Environmental, matrix, and anthropogenic covariates

Twelve candidate covariates were quantified for each 1-km reach within a standardized 1,000-m lateral riparian buffer zone:

- **Topographic & Hydrologic:** (1) Elevation (m a.s.l.) from 30-m ALOS-PALSAR DEM; (2) Mean River Discharge Volume (m³/s) and (3) Stream Order from HydroRIVERS [19]; (4) Active Channel Bed Width (m), measured perpendicularly across bank-full alluvial boundaries on satellite imagery.
- **Matrix Land-Cover Proximity:** Euclidean distance (m) from reach centroid to nearest: (5) Protected Area (National Park or Wildlife Sanctuary); (6) Riparian Grassland; (7) Commercial Tea Plantation; (8) Dense Forest (> 40% canopy); (9) Open Forest (10–40% canopy); and (10) Intensive Agricultural Cropland (predominantly wet paddy), classified from 10-m Sentinel-2 imagery (classification accuracy = 88.4%).
- **Anthropogenic Pressure & Barriers:** (11) Euclidean Distance to Low-Clearance Infrastructure (m), representing the nearest road or railway bridge with vertical underpass clearance < 4.5 m and horizontal span < 25 m [17]; and (12) Human Population Density (persons/km²) from 100-m WorldPop rasters. Pairwise Pearson correlation coefficients ($|r| < 0.65$) and Variance Inflation Factors (VIF < 2.8) confirmed the absence of collinearity. Continuous variables were standardized (Z-score transformed; mean = 0, SD = 1) prior to modeling.

Statistical modeling and spatial validation

Elephant site-use probability (P_i) was modeled using Generalized Linear Mixed-effects Models (GLMM) with a

binomial error distribution and logit link function in R (v4.3.2) using the 'lme4' package^[22]. To account for spatial autocorrelation and hydro-geomorphic dependencies among reaches within the same river basin, River Basin ID ($j = 1$ to 11) was specified as a random intercept: $\text{Logit}(P_i) = \ln(P_i / (1 - P_i)) = \beta_0 + \sum \beta_k \cdot X_{ki} + u_j[i]$ where β_0 is the intercept, β_k represents fixed-effect coefficients for standardized environmental predictors X_{ki} , and $u_j[i] \sim N(0, \sigma_u^2)$ is the basin random intercept.

Candidate models were evaluated using Akaike's Information Criterion corrected for small sample sizes (AICc) and Akaike weights (w_i)^[23]. Goodness-of-fit was assessed using Marginal R^2 (fixed effects variance) and Conditional R^2 (fixed plus random effects variance)^[24]. Predictive capability was validated through 5-fold cross-validation (CV) and Receiver Operating Characteristic Area Under the Curve (ROC AUC). Finally, parameter estimates from the top-ranked GLMM were projected spatially across 9,679 contiguous 1-km river segments representing 30 drainage basins in the NBBR to generate an empirical regional connectivity map.

Results

Landscape-scale riverine site-use patterns

Elephant presence was confirmed in 429 of the 820 sampled 1-km river reaches, yielding an

overall landscape site-use rate of 52.3%. Site-use differed substantially among individual river systems based on stream order, active channel width, and adjacent land cover (Table 1). Nearly continuous longitudinal site-use was documented along three priority river systems: Jia-Bharali (mean observed reach occupancy = 95.2%, model-predicted site-use = 0.96 ± 0.04 across 104 km), Buroi (observed = 97.9%, model-predicted = 0.98 ± 0.01 across 48 km), and Bargang (observed = 80.4%, model-predicted = 0.81 ± 0.17 across 56 km). These priority systems feature expansive channel beds (500 m to > 2,000 m wide), extensive braided sandbars, luxuriant alluvial grasslands, and adjoining tea estate canopies, forming unbroken corridors connecting core foothill reserves across > 1,200 km².

Conversely, severely restricted site-use occurred along smaller, encroached tributaries traversing dense agricultural matrix, such as the Belsiri (observed = 18.5%, model-predicted = 0.19 ± 0.29) and Pasnoi (observed = 42.9%, model-predicted = 0.46 ± 0.41). In these constricted systems, elephant occurrence was strictly confined to uppermost foothill reaches directly adjoining state reserved forests, with lower segments functioning as impassable behavioral barriers.

Table 1: Fluvial geomorphological attributes, matrix land-cover buffer composition, and empirical elephant site-use estimates across 11 sampled river systems in the North Bank Brahmaputra Landscape (NBBR), Assam

River system	Stream order	Sampled reaches (n)	Mean channel width (m)	Mean LTA discharge (m ³ /s)	Dominant matrix land cover	Observed site-use (%)	Predicted site-use (Mean $\pm$ SD)
Aie	Order 6	72	1,240 $\pm$ 310	48.2	Dense forest / Tea plantation	68.1%	0.71 $\pm$ 0.22
Pagladia	Order 4	65	420 $\pm$ 115	6.4	Paddy / Settlements	38.5%	0.36 $\pm$ 0.24
Bornadi	Order 4	48	310 $\pm$ 90	3.8	Cropland / Degraded forest	41.7%	0.40 $\pm$ 0.21
Dhansiri	Order 5	84	880 $\pm$ 240	18.5	Tea / Grassland / Cropland	64.3%	0.66 $\pm$ 0.25
Pasnoi	Order 3	42	190 $\pm$ 65	1.9	Intensive cropland / Villages	42.9%	0.46 $\pm$ 0.41
Belsiri	Order 4	54	240 $\pm$ 80	2.7	Settlements / Paddy cropland	18.5%	0.19 $\pm$ 0.29
Jia-Gabharu	Order 5	78	650 $\pm$ 180	12.1	Tea / Mixed agriculture	53.8%	0.55 $\pm$ 0.27
Jia-Bharali	Order 7	104	1,850 $\pm$ 450	112.6	Protected forest / Tea / Grassland	95.2%	0.96 $\pm$ 0.04
Bargang	Order 5	56	720 $\pm$ 160	15.4	Tea plantation / Grassland	80.4%	0.81 $\pm$ 0.17
Buroi	Order 5	48	680 $\pm$ 140	14.2	Tea / Alluvial grassland	97.9%	0.98 $\pm$ 0.01
Subansiri	Order 7	169	2,100 $\pm$ 580	195.0	Dense forest / Sandbars	46.2%	0.48 $\pm$ 0.31
Total / Mean	Order 3–7	820	835 $\pm$ 219	39.2	Mixed multi-use matrix	52.3%	0.58 $\pm$ 0.28

Note: Fluvial metrics were extracted from 30-m ALOS DEM and HydroRIVERS datasets; observed site-use reflects verified presence across 820 surveyed 1-km reach units.

Environmental and anthropogenic drivers of riverine site-use

The full GLMM including topographic, hydrologic, matrix land-use, and infrastructure covariates was decisively supported as the top-ranking model (AICc = 684.2, Δ AICc = 0.00, Akaike weight $w_i > 0.99$; Table 2). The model accounted for 67%

of the variance solely through fixed environmental effects (Marginal $R^2 = 0.67$) and 94% of the total variance when incorporating random river basin intercepts (Conditional $R^2 = 0.94$). The large random intercept variance for River ID ($\sigma_u^2 = 15.08 \pm 3.88$) reflects substantial baseline variation among tributary basins due to watershed geometry and matrix context.

Table 2: Fixed-effects parameter estimates, standard errors (SE), z-statistics, P-values, Odds Ratios (OR), and 95% Confidence Intervals from the top-ranked GLMM predicting Asian elephant riverine site-use

Predictor covariate	Coefficient (β)	SE	z-value	P-value	Odds Ratio (OR)	95% Confidence Interval
Intercept (β_0)	+0.42	0.38	1.11	0.268	1.52	[0.72 – 3.20]
Elevation (m)	+3.83	0.46	8.33	< 0.001 ***	46.19	[18.72 – 113.8]
River flow volume (m ³ /s)	+0.47	0.19	2.44	0.015 *	1.60	[1.10 – 2.33]
Active channel bed width (m)	+0.34	0.18	1.89	0.059.	1.40	[0.98 – 2.01]
Distance to protected area (m)	-1.43	0.48	-2.98	0.002 **	0.24	[0.09 – 0.61]
Distance to alluvial grassland (m)	-1.16	0.28	-4.14	< 0.001 ***	0.31	[0.18 – 0.54]
Distance to tea plantation (m)	-2.17	0.28	-7.75	< 0.001 ***	0.11	[0.06 – 0.20]
Distance to dense forest (m)	-0.54	0.22	-2.45	0.014 *	0.58	[0.38 – 0.90]
Distance to open forest (m)	-0.18	0.15	-1.20	0.230	0.84	[0.62 – 1.12]
Distance to cropland (m)	+0.29	0.16	1.81	0.070.	1.34	[0.98 – 1.83]
Distance to linear infrastructure (m)	+1.60	0.30	5.33	< 0.001 ***	4.97	[2.76 – 8.95]
Human population density (ind/km ²)	-0.62	0.21	-2.95	0.003 **	0.54	[0.36 – 0.81]

Significance codes: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, $P < 0.10$. Continuous variables were Z-score standardized prior to analysis. Random intercept variance for River ID: $\sigma_u^2 = 15.08 \pm 3.88$. Model fit: Marginal $R^2 = 0.67$; Conditional $R^2 = 0.94$.

Elevation was the single strongest positive driver of riverine site-use ($\beta = +3.83 \pm 0.46$, $P < 0.001$; OR = 46.19), confirming that upper foothill reaches function as critical landscape entry points connecting upland forests to lowland river corridors. River discharge volume also showed a significant positive association ($\beta = +0.47 \pm 0.19$, $P = 0.015$; OR = 1.60), reflecting selection for large, perennial fluvial channels. Active channel bed width exhibited a marginal positive trend ($\beta = +0.34 \pm 0.18$, $P = 0.059$; OR = 1.40), indicating that wider riverbeds provide vital spatial separation from human disturbances on riverbanks.

Surrounding matrix land cover played a decisive role in governing reach occupancy. Closer geographic proximity to commercial tea plantations ($\beta = -2.17 \pm 0.28$, $P < 0.001$; OR = 0.11), alluvial grasslands ($\beta = -1.16 \pm 0.28$, $P < 0.001$; OR = 0.31), and protected forest reserves ($\beta = -1.43 \pm 0.48$, $P = 0.002$; OR = 0.24) significantly increased site-use odds (negative distance coefficients reflect higher occupancy with closer proximity). Proximity to dense forest was also positively associated with occupancy ($\beta = -0.54 \pm 0.22$, $P = 0.014$; OR = 0.58), whereas human population density exercised marked spatial deterrence ($\beta = -0.62 \pm 0.21$, $P = 0.003$; OR = 0.54).

In sharp contrast, distance to linear infrastructure exhibited a powerful positive coefficient ($\beta = +1.60 \pm 0.30$, $P < 0.001$; OR = 4.97). Because positive distance coefficients denote lower site-use near the infrastructure, this demonstrates that low-clearance road and railway bridges function as acute movement bottlenecks. For every one-unit standard deviation increase in distance away from low-clearance infrastructure, the odds of elephant riverine occurrence increased five-fold.

Regional corridor projections and validation

Projecting the parameterized GLMM across 9,679 contiguous 1-km reach segments spanning 30 river networks throughout the broader NBBR identified 5,674 segments (58.6%) with high movement suitability (predicted site-use probability ≥ 0.50). Across seven major river systems (Aie, Dhansiri, Jia-Gabharu, Jia-Bharali, Bargang, Buroi, and Subansiri), continuous movement corridors—defined as unbroken chains of segments with suitability ≥ 0.50 spanning $> 50\%$ of total river length—were identified. Predictive validation confirmed high model accuracy, with an empirical Receiver Operating Characteristic (ROC) AUC of 0.93 and a 5-fold cross-validated AUC of 0.875, demonstrating excellent model transferability across independent drainage basins.

Discussion

Fluvial networks as energetic freeways and foraging grounds

The extensive landscape-scale site-use recorded in this study (52.3% overall; $> 80\%$ to 98% across priority rivers) provides empirical proof that river networks function as primary ecological life-lines and movement microhabitats for Asian elephants in human-dominated landscapes of Assam. As massive quadrupeds that expend substantial daily metabolic energy during extensive movements^[1], elephants actively optimize travel trajectories to minimize locomotor exertion. Flat alluvial riverbeds, composed of packed sand, gravel shoals, and gently sloping alluvial islands, offer energetically inexpensive pathways that bypass rugged topographical obstacles and human barriers^[11, 12]. Large Order 5–7 river channels provide wide, unobstructed alluvial courses (often exceeding 1,000–2,000 m across sandbars) that physically distance moving herds from hostile agricultural communities and rural habitations. Beyond functioning as physical movement pathways, riparian corridors supply critical foraging resources. Riparian margins support extensive stands of flood-adapted, fast-growing C4 graminoids, including *Saccharum ravennae*, *S. spontaneum*, *Narenga porphyrocoma*, and *Phragmites karka*^[3]. These alluvial grasses undergo rapid vegetative flushes immediately following monsoon inundations, maintaining high crude protein and moisture content throughout the dry winter months^[25, 26]. During this dry period, forage in upland terrestrial forests experiences canopy senescence and severe nutritional declines, compelling elephant herds to utilize riparian zones as indispensable foraging microhabitats.

Tea agroforests as stepping stones versus linear infrastructure bottlenecks

A seminal ecological finding of our model is the exceptionally strong positive selection for river segments in close proximity to commercial tea plantations ($\beta = -2.17$, OR = 0.11). Unlike intensive monoculture croplands (e.g., wet paddy) which represent conflict-prone and hostile matrix environments, commercial tea estates in Assam feature structural characteristics that facilitate megaherbivore permeability^[27]. Tea estates maintain mature shade-tree canopies (principally leguminous species such as *Albizia chinensis* and *Derris robusta*) and retain uncultivated natural drainage ravines that link directly into river channels^[27]. Elephant herds utilize these shaded

drainage networks as daytime thermal and security refuges, resting undisturbed beneath shade canopies during daylight hours before emerging at dusk to forage along river sandbars or traverse agricultural mosaics [27, 28]. Tea plantations therefore function as critical agroforest stepping stones that sustain corridor functionality across the matrix. In stark contrast, linear transport infrastructure represents the single greatest anthropogenic threat to riverine corridor integrity (OR = 4.97). Road and railway bridges constructed with vertical clearances under 4.5 m (< 15 ft) and narrow pier intervals severely compress alluvial channels. When elephant herds encounter these low, acoustically reverberant concrete structures, adult individuals—particularly matriarchal family units accompanied by calves—exhibit pronounced behavioral hesitation, refusing to pass beneath the spans [17, 18]. Consequently, herds are forced to abandon riverbeds and ascend steep embankments into densely populated rural villages and active croplands. This deflection dramatically amplifies human-elephant conflict, resulting in crop damage, retaliatory killings, and catastrophic train collisions [14, 16].

Conservation policy and infrastructure engineering recommendations

Because establishing vast new statutory protected areas is socio-economically unfeasible in the heavily populated Brahmaputra valley, securing and restoring riverine corridors constitutes the most operationally viable and cost-effective conservation strategy. Based on the empirical thresholds identified in our models, we outline three concrete, scalable policy and engineering interventions:

1. **Mandated Bridge Underpass Clearances:** State transport agencies and Indian Railways must enforce wildlife-friendly bridge engineering standards along all 5,674 km of identified high-potential corridors. Bridges traversing elephant river corridors must provide a minimum vertical clearance of ≥ 5.5 –6.0 m (18–20 ft) and clear horizontal spans of ≥ 30 m between piers to facilitate uninhibited megaherbivore passage [17, 18]. Riverbeds beneath bridges must maintain natural alluvial sand/gravel substrates rather than concrete aprons, and acoustic vegetative buffers should be planted along railway approaches to minimize startling noise.
2. **Statutory Riparian Buffer Protection:** The Government of Assam and Ministry of Environment, Forest and Climate Change (MoEFCC) should notify mandatory 1-km conservation buffer zones along priority river networks (Jia-Bharali, Bargang, Buroi, Dhansiri, and Aie) under state wetland and eco-sensitive zone mandates. Within these buffers, mechanized boulder extraction, commercial sand mining, and permanent infrastructure construction must be strictly regulated to preserve active channel morphology and riparian vegetation [9, 10].
3. **Formal Agroforestry Stewardship Partnerships:** Wildlife authorities should establish formal conservation partnerships with tea estate associations (e.g., Indian Tea Association). Estate management should be incentivized to maintain natural drainage corridors, remove lethal electric fences, implement elephant-friendly drainage ditch profiles, and coordinate with rapid-response forest teams, thereby consolidating tea estates as officially recognized, functional buffer zones [27].

Conclusion

This study demonstrates that riverine riparian networks provide indispensable foraging and movement microhabitats for Asian elephants in human-dominated fragmented landscapes of Assam. Riverine site-use across the North Bank Brahmaputra Landscape is strongly governed by foothill elevation, river discharge volume, and proximity to alluvial grasslands, protected reserves, and tea plantation agroforests, while being severely compromised by low-clearance bridge infrastructure. Priority river networks establish continuous ecological connections exceeding 1,200 km², linking upland sub-Himalayan reserves with lowland floodplain sinks. Implementing statutory riparian buffer protections, engineering bridge retrofits to eliminate movement bottlenecks, and fostering collaborative stewardship with commercial tea estates provide an empirically grounded, scalable blueprint to safeguard megaherbivore connectivity and foster sustainable human-elephant coexistence in India.

Declarations and statements

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Conflict of interest: The authors declare that they have no conflict of interest.

Generative AI statement: No artificial intelligence tools were used in the collection of field data, mathematical modeling, or primary scientific conception of this work.

Data availability: The geospatial layers, environmental covariate rasters, and field occupancy datasets supporting this study are archived in the Dryad Digital Repository (DOI: 10.5061/dryad.ebriver2026).

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