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Movement ecology and habitat preferences of translocated greater one-horned rhinoceros in their historic range in Nepal

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A R T I C L E I N F O

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A B S T R A C T

The greater one-horned rhinoceros (*Rhinoceros unicornis*, hereafter, rhinos) has lost much of its historical range and now survives only in a few isolated protected areas in Nepal and India. Listed as 'Vulnerable' on the IUCN Red List and in Appendix I of CITES, it remains one of the most threatened megaherbivores. To restore populations within their former range, Nepal has translocated rhinos from Chitwan National Park (NP) to Bardia and Shuklaphanta NP since 1986. In 2016/17, eight individuals were released in the Babai Valley of Bardia NP, five of which were fitted with GPS collars programmed to record hourly locations. Despite these efforts, the habitat use and spatial distribution patterns of translocated rhinos have remained poorly understood, despite being crucial for ecological sustainability. In this study, we analyzed 24,014 GPS fixes to map fine-scale habitats, estimate home ranges, and assess movements and habitat uses. Annual and seasonal home ranges were calculated using the Fixed Kernel (95%) method in Home Range Tools (ArcMap 10.3). Habitat preference was examined by overlaying GPS locations with classified Sentinel-2A imagery (10 m resolution). The average home range of collared individuals was 11.61 km^2, ranging from 15.07 km^2 during the dry season to 5.35 km^2 in the monsoon season. Average daily movement ranged from 2.71 $\pm$ 0.12 km to 4.34 $\pm$ 0.30 km. Spatial analyses revealed that grasslands (45.47%) were the most used habitat, followed by riverine forests (21.93%) and water bodies (13.53%), while *Shorea robusta* (Sal) and mixed forests were the least used (6.97%). These findings provide critical insights into habitat use and movement ecology, highlighting the need for habitat-specific management, seasonal connectivity, and grassland restoration to guide long-term rhino reintroduction programs across their historical range.

1. Introduction

Rhinoceros species—one of the largest megaherbivores—are only restricted to the African and Asian continents in the Anthropocene (Janssens and Trouwborst, 2018; Ripple et al., 2015). Their distribution is distinguished by the number of horns, body coloration, and size in natural habitats. These include two African species, the white rhino and the black rhino, and three Asian species, the greater one-horned rhino (*Rhinoceros unicornis*, hereafter 'rhinos'), the Sumatran rhino, and the Javan rhino (Amin et al., 2006; Laurie, n.d.). Historically, the rhinos ranged widely across the floodplains of the Ganges, Brahmaputra, and Indus rivers (Laurie, 1982; Pant et al., 2020). At present, however, its range has been shrunk to a patchy distribution in southern Nepal and northern and northeastern India, with isolated populations in a few protected areas and adjoining forests (Pant et al., 2022; Steinheim et al., 2005). The species has been listed as 'Vulnerable' on the IUCN Red List

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since 2008 (IUCN, 2025; Talukdar et al., 2025) and is included in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which prohibits all international trade of live animals or their parts (CITES, 1973; GoN, 2016). Due to intensive protection measures over the past decades, the rhino population has recovered from approximately 200 individuals to nearly 4,000 between 1900 and 2020 (Mukherjee et al., 2020), and more than 6000 wild rhinos at the moment (Jhala et al., 2021; Talukdar et al., 2025), reflecting the success of conservation efforts implemented by communities, governments, and international collaborations (Pant et al., 2020).

The rhinos are a morphologically unique, threatened species, primarily due to habitat loss, degradation, and poaching (Arbogast and Dinerstein, 2017). As an ecological landscaper, the species influences habitat structure, ecosystem processes, and community diversity (Gordon et al., 2004; Sinclair, 2003). Tall floodplain grasslands, interspersed with riverine forests and wetlands, are considered critical habitats for rhinos (Arbogast and Dinerstein, 2017; Dinerstein, 1992; Subedi et al., 2013).

In Nepal, rhinos are legally protected under the National Parks and Wildlife Conservation Act, 1973, which prohibits their use or trade (GoN, 2016, 1973). Historically widespread across the lowland Terai, the species was confined to Chitwan National Park by the 1950 s, following extensive hunting and land conversion (Laurie, 1982). Subsequent reintroductions expanded their distribution to Bardia and Shuklaphanta National Parks (NPs), while natural dispersal extended into Parsa NP (DNPWC, 2023, 2022). A recent survey shows that there are 752 rhinos occurring in the wild in four lowland protected areas and adjoining forests of Nepal (DNPWC, 2023). Chitwan NP, a UNESCO World Heritage Site (Lehmkuhl, 1994; Pandey et al., 2025a), supports the largest population (694 individuals) and serves as the source for all other populations in Nepal (DNPWC, 2023; Subedi et al., 2013). Smaller populations persist in Bardia NP and its surroundings (n = 38) and Shuklaphanta NP and its surroundings (n = 17) (DNPWC, 2023).

As a conservation-dependent species, rhinos require continuous protection, active management, and regular monitoring of their behaviors in the newly introduced habitats to ensure their long-term survival (Pant et al., 2022; White et al., 2007; White and Garrott, 2012; Worton, 1989). In addition to strict protection, biological management tools such as captive breeding, reintroductions, and translocations have become increasingly important (Ebenhard, 1995; Ripple et al., 2015). These interventions reduce risks of local extinction from catastrophic events, disease, and poaching (Laurie, 1982; Thapa et al., 2013). Notable examples include white rhinos (*Ceratotherium simum*) reintroductions in Botswana (Janssens and Trouwborst, 2018; Ripple et al., 2015) and the greater one-horned rhinos in Dudhwa Tiger Reserve, India (Jhala et al., 2021). In Nepal, 100 rhinos were translocated from Chitwan NP to Bardia NP (n = 91) and Shuklaphanta NP (n = 9) between 1986 and 2003 (n = 87) and 2016 and 2017 (n = 13), aiming to establish viable populations in these parks. Between 2016 and 2017, eight rhinos were released in the Babai Valley Areas of Bardia NP, of which five were fitted with satellite radio collars (DNPWC, 2023, 2022; Pant et al., 2020).

In this context, we aim to analyze the movement ecology, habitat preferences, and seasonal and average home ranges of radio-collared rhinos based on GPS location data, to inform policy decisions and practical actions for the long-term sustainability of this vulnerable species in its historical habitats. This study offers three key innovations: (1) it presents the first fine-scale GPS-based analysis of reintroduced rhinos in Nepal, generating over 24,000 location points; (2) it reveals novel seasonal and sex-specific variations in home ranges and habitat use, with management implications for small, reintroduced populations; and (3) it provides actionable policy guidance on grassland restoration, water management, and population supplementation to strengthen long-term reintroduction strategies. Together, these contributions advance scientific understanding of rhino movement ecology while offering practical lessons for sustaining megaherbivores in fragmented landscapes globally.

2. Methods

2.1. Study area

Babai Valley, as a significant habitat inside the Bardia NP, located in the western lowland Terai of Nepal, covers an area of 968 km^2 (Fig. 1) (BNP, 2025; Thakur et al., 2025). The park has a subtropical monsoonal climate with three distinct seasons: monsoon (June–September), winter (October–February), and dry (March–May) (Weather and Climate, 2025). The monthly mean temperature ranges from a minimum of 10 °C in January to a maximum of 45 °C in June. Annual rainfall varies between 1,560 and 2,230 mm, with the majority occurring during the monsoon season (Weather and Climate, 2025). Two major river systems, the Karnali and Babai, flow through the park.

This study was conducted in the Babai Valley, located in the north-eastern part of Bardia NP (81°22′32.412″E to 81°42′46.512″E; 28°20′9.1284″N to 28°33′16.8552″N). The Babai Valley (~350 km2) was incorporated into the park in 1984. Major vegetation communities include riverine forests and discrete patches of grassland—locally known as *phantas*—along the Babai River and its tributaries, mixed subtropical forests, and climax Sal (*Shorea robusta*) forests. The valley supports rich faunal diversity, including the rhinos (*Rhinoceros unicornis*), Royal Bengal tiger (*Panthera tigris tigris*), Asian elephant (*Elephas maximus*), sambar deer (*Rusa unicolor*), spotted deer (*Axis axis*), and numerous other wildlife species (BNP, 2025).

The grasslands in the study area consist of tall grasslands, short grasslands in *phantas* (natural vegetation growing on previously cultivated dry fields), and wooded grasslands with scattered tree species. In the study area, the dominant tree species are *S. robusta*, accompanied by associated species such *as Terminalia tomentosa, Terminalia chebula, Lagerstroemia parviflora,* and *Buchanania latifolia*. The other major tree species in riverine habitats include *Mallotus philippensis, Syzygium cumini, Ficus glomerata, Acacia catechu,* and *Dalbergia sissoo*. Streambeds and exposed surfaces of sand, gravel, and boulders occur along the Babai River and its tributaries, both permanent and seasonal. Water sources in the valley include the Babai River, its tributaries, artificial waterholes, natural waterholes, and small marshy areas (BNP, 2025).

2.2. Data collection

Eight rhinos were reintroduced into the Babai Valley of Bardia National Park from Chitwan NP, of which five individuals (three females, two males; Table 1) were fitted with Vectronic Aerospace satellite collars to monitor post-release movements and habitat use. All reintroduced rhinos were adults (12–20 years), physically vigorous, and their health was assessed by veterinary staff before translocation. Following release, rhinos were monitored at least three times daily, and all adapted well within weeks. Four collared rhinos were released in March 2016, with an additional individual in April 2017. Hourly GPS locations, collected over five to eleven months by the Department of National Parks and Wildlife Conservation, formed the primary dataset (*please refer to the data availability statement in the annex for more details*). Habitat use and preference were analyzed by overlaying rhino locations onto Sentinel-2A satellite-derived land cover maps at 10 × 10 m^2 resolution.

2.3. Data analysis

2.3.1. Home range estimation

GPS locations of each rhinoceros, recorded at one-hour intervals from the radio collars, were used for home range estimation. Home ranges were calculated using the Home Range Tools (HRT) add-on in ArcGIS 10.3. GPS fixes were screened for outliers, and kernel methods were applied with awareness of temporal autocorrelation. Limitations of hourly fixes are acknowledged in the last part of the discussion section.

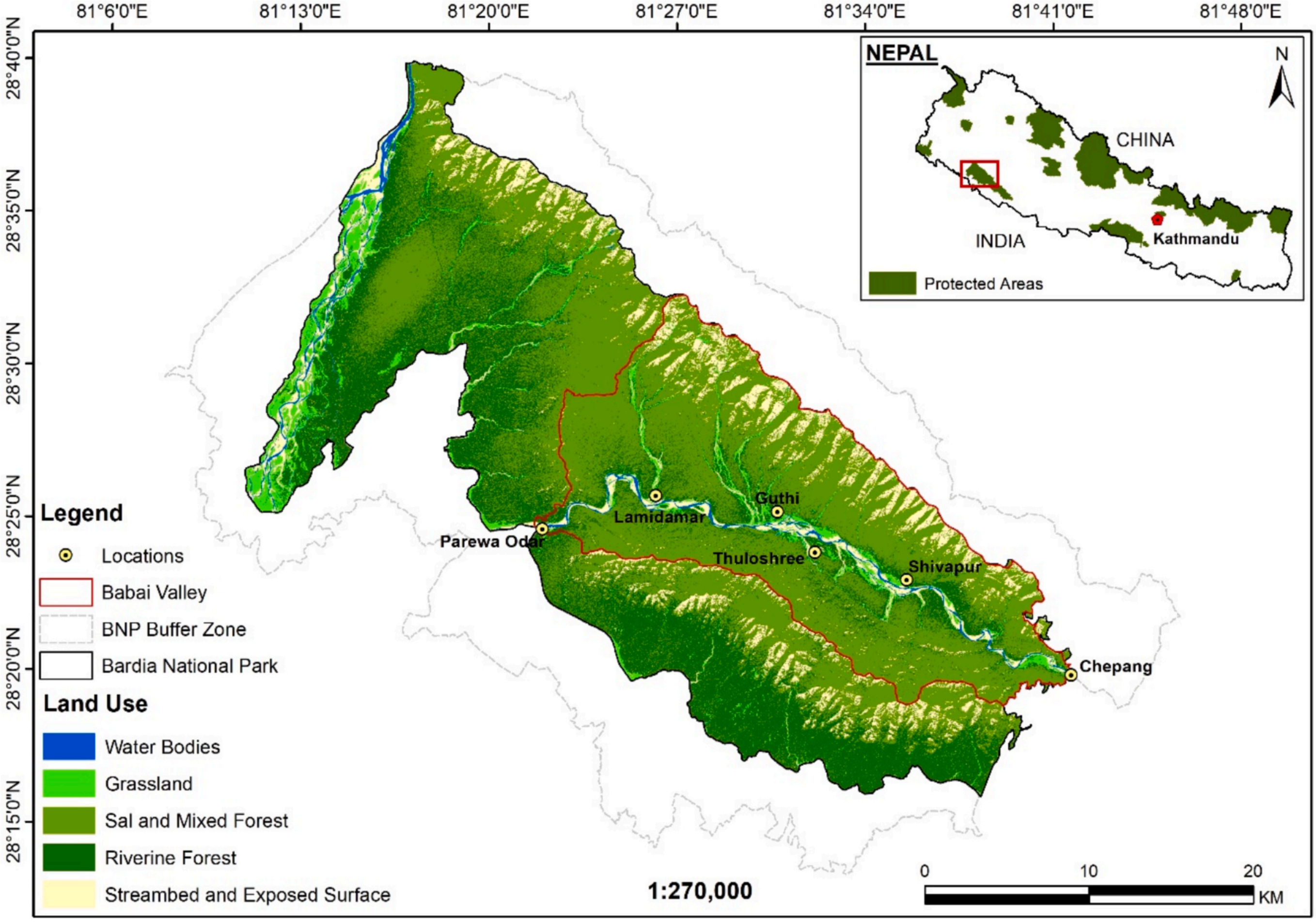

Fig. 1. Babai catchment in the Bardia National Park.

Table 1
Number of days tracked for five GPS-collared rhinos in Bardia National Park between March 2016 and April 2017.

Rhino ID	Sex	Total data days	Start date	End date	Total location used	Season-wise data days		
						Hot dry	Monsoon	Cool dry
21,009	Male	329	3/10/2016	2/2/2017	7461	97	122	110
21,010	Female	162	3/4/2016	8/13/2016	3620	103	59	–
21,011	Male	206	3/4/2016	9/26/2016	4637	103	103	–
21,012	Female	208	3/5/2016	9/29/2016	4976	102	106	–
21,013	Female	139	4/10/2017	8/27/2017	3320	66	73	–
Total					24,014	471	463	110

The GPS fixes with positional error more than 20 m were excluded from the analysis. To avoid autocorrelation and consistency in the data, we resampled high-resolution (1/2 h interval) data of some rhinos into 1-hour intervals. For the kernel bandwidth (smoothing parameter), we followed the procedure as suggested by Subedi et al. (2013). Two non-parametric methods—the Minimum Convex Polygon (MCP) (Mohr, 1947) and the fixed Kernel Density (KD) (Worton, 1989)—were applied to estimate seasonal and overall home range sizes. The 95% MCP sub-sampling was applied to exclude extreme outliers and avoid seasonal bias, with randomization across seasons. For this, we calculated 95% MCP in HRT tools using the fixed mean method, which calculates the arithmetic mean of all x (longitude) and y (latitude) co-ordinates, then selects 95% of points closest to that arithmetic mean point.

Seasonal home ranges were analyzed for the hot-dry (mid-February to mid-June), monsoon (mid-June to mid-October), and cool-dry (mid-October to mid-February) periods, based on available data. If data were not available for a particular season, analyses were discarded for that season for the data-deficient rhino. MCPs are sensitive to extreme locations, as they fully enclose all points by connecting the outermost locations to form a convex polygon (Boitani and Fuller, 2000). To reduce the influence of random movements, 95% MCPs were estimated using 95% of randomly selected locations. Although MCPs may overestimate home ranges, they help explain why individuals occupy certain areas while avoiding others (White et al., 2007) and allow comparison with previous MCP-based studies (Thakur et al., 2025). Similarly, a 95% fixed kernel, which minimizes the effect of exploratory movements and outlier fixes (Kernohan et al., 2001; White and Garrott, 2012), was used for a more precise estimation of home range. The kernel density method is widely used due to its robustness and convenience, especially with large GPS datasets (Kie et al., 2010). While both MCPs and Kernel home ranges were calculated, interpretation and comparisons were primarily based on the 95% kernel estimates.

2.3.2. Movement pattern

Daily and seasonal movements were analyzed using the Home Range Tools (HRT) add-on in ArcGIS 10.3, based on GPS collar locations of individual rhinos. Daily movement tracks were generated, starting from midnight to the next midnight, using precise time-based collar data. The distance traveled in a day was calculated from the movement track generated for each day. The results present the average distance traveled by every individual per day, as well as diurnal and nocturnal movement patterns. Movement estimates from HRT tracks were based on Euclidean step-lengths calculated from hourly GPS fixes. Terrain-induced path correction was not applied, as hourly intervals minimized cumulative spatial error. However, if the data does not cover three seasons of the year, the data-deficient season was discarded while calculating the mean daily and day-night movement. For the day-night analysis of the data, 6 AM to 5:59 PM was considered as daytime, and dusk to dawn (6 PM to 5:59 AM) was considered as nighttime.

2.3.3. Habitat uses

Habitat used by the reintroduced rhinos was evaluated by overlaying the rhinos' location data on the park's land cover map. The land cover was classified using a cloud-free Sentinel-2A satellite image from November 30, 2017. Five dominant land cover categories were identified: water bodies, stream and exposed surfaces, grassland, riverine forest, and *Shorea robusta* (Sal) and mixed forest, based on training samples collected during the field study. A total of 427 sample field points were collected from the Babai valley for the land cover classification under 6 land cover categories (Water bodies, Riverbed, Grassland, Riverine Forest, Sal and Mixed Forest, and Exposed surfaces). The samples were divided into classification signatures ($n = 277$) and error matrix testing samples ($n = 150$). After classifying the riverbed and exposed surface, these classes were merged to make single class categories.

Classification and accuracy assessment were conducted in ArcGIS 10.3 using Maximum Likelihood Classification and the Confusion Matrix tool. The overall accuracy of the supervised classification was 97.30%, with a Kappa coefficient of 0.95. Habitat use was calculated using the exact locations recorded for each rhino rather than the MCP or Kernel Density home range, to minimize inclusion of unused areas. Nevertheless, the coverage of different land cover types within the rhinos' home ranges was also presented on maps alongside home range estimates. Analyses included overall habitat use, daytime and nighttime habitat use, and seasonal habitat use, with seasonal patterns assessed using chi-square tests. All spatial analyses are reproducible using raw hourly GPS fixes and Sentinel-2A classified raster layers, without color-based symbology affecting outputs. Additionally, apart from the radio-collaring data, habitat classification layers and accuracy assessment outputs are included. A text file containing the parameters used for the HRT Kernel Density Estimation analysis is provided as a supplementary file (S1).

3. Results

A total of 24,014 GPS locations were obtained from five radio-collared rhinos between 2016 and 2017 (over a period of five to eleven months), of which 12,098 belonged to males and 11,916 to females (Table 1). The GPS data were collected over an average of 208.8 days per individual, ranging from 139 to 329 days.

3.1. Overall and seasonal home range

Kernel density home ranges (km^2) of five reintroduced greater one-horned rhinos in the Babai Valley, Bardia National Park. Individual kernel home ranges ranged from 3.15 to 19.45 km^2, with a mean ($\pm$ SD) of 11.62 $\pm$ 6.99 km^2 (Table 2). Male rhinos exhibited home ranges of 3.15 and 14.23 km^2, whereas females occupied larger and more variable ranges (19.45, 15.80, and 5.45 km^2). The mean minimum convex polygon (MCP) home range was 32.89 km^2. Seasonal differences were evident, with a larger mean home range during the hot-dry season (15.07 km^2) compared with the monsoon season (5.34 km^2) (Fig. 2).

3.2. Movement pattern of reintroduced rhinos

The average daily distance traveled by rhinoceroses ranged from 2.714 $\pm$ 0.124 km/day to 4.335 $\pm$ 0.296 km/day (95% confidence interval). Daily movement was generally higher in the dry season than in the monsoon season, except for ID 21009. Similarly, nocturnal movement exceeded daytime movement for most individuals, except for ID 21010. Hourly analysis revealed peak movements in the early morning (05:00–07:00) and evening (19:00–21:00) periods, with an exceptional midday movement observed for ID 21011 between 12:00 and 15:00 (Fig. 3). Data for the cool-dry season were available only for ID 21009 and were excluded from the analysis (Table 3).

3.3. Habitat preference by reintroduced rhinos

The most frequently used habitat by all reintroduced rhinos was grassland (45.47%), followed by riverine forest (21.93%), water bodies (13.53%), and streambeds and exposed surfaces (12.1%) (Fig. 4). Sal and mixed forests were the habitats least used (6.97% (Table 4).

3.4. Seasonal habitat preferences

During the hot-dry season, grassland was the dominant habitat used by rhinos (39.29 $\pm$ 4.81%), followed by riverine and mixed forest (21.26 $\pm$ 10.66%), water bodies (19.36 $\pm$ 7.10%), streambeds and exposed surfaces (13.30 $\pm$ 5.39%), and *Shorea robusta* and other forests (6.78 $\pm$ 2.85%). In the monsoon season, grassland use increased markedly (51.96 $\pm$ 9.84%), while riverine and mixed forest accounted for 23.25 $\pm$ 15.14% of habitat use. Streambeds and exposed surfaces (9.75 $\pm$ 4.31%), water bodies (7.33 $\pm$ 3.50%), and Sal and other forests (7.70 $\pm$ 2.56%) were used comparatively less (Table 5). Habitat use was followed by riverine forest, comprising 21.26% and 23.25% of use in the respective seasons. *S. robusta* and mixed forests were the least preferred habitats across both seasons (Fig. 5).

4. Discussion

Overall, translocation of greater one-horned rhinos to the Babai Valley of Bardia National Park provided valuable insights into post-

Table 2
Overall and seasonal home ranges of individual rhinos in Babai Valley inside Bardia NP.

Rhino ID	Sex	No. of location	Home Range 95% Karnel	Season-wise Home Range 95% Kernel			95%MCP	Season-wise Home Range 95% MCP		
				Hot dry	Monsoon	Cool dry		Hot dry	Monsoon	Cool dry
21,009	Male	7461	3.15	3.36	3.68	5.78	6.94	4.02	3.33	7.15
21,011	Male	4637	14.23	15.84	11.92	–	21.27	19.62	14.72	–
21,010	Female	3620	15.80	24.00	0.75	–	86.56	86.80	0.65	–
21,012	Female	4976	19.45	25.55	8.26	–	41.02	42.44	13.14	–
21,013	Female	3320	5.45	6.62	2.12	–	8.67	9.34	2.59	–
Overall			11.61	15.07	5.35	5.78	32.89	32.44	6.89	

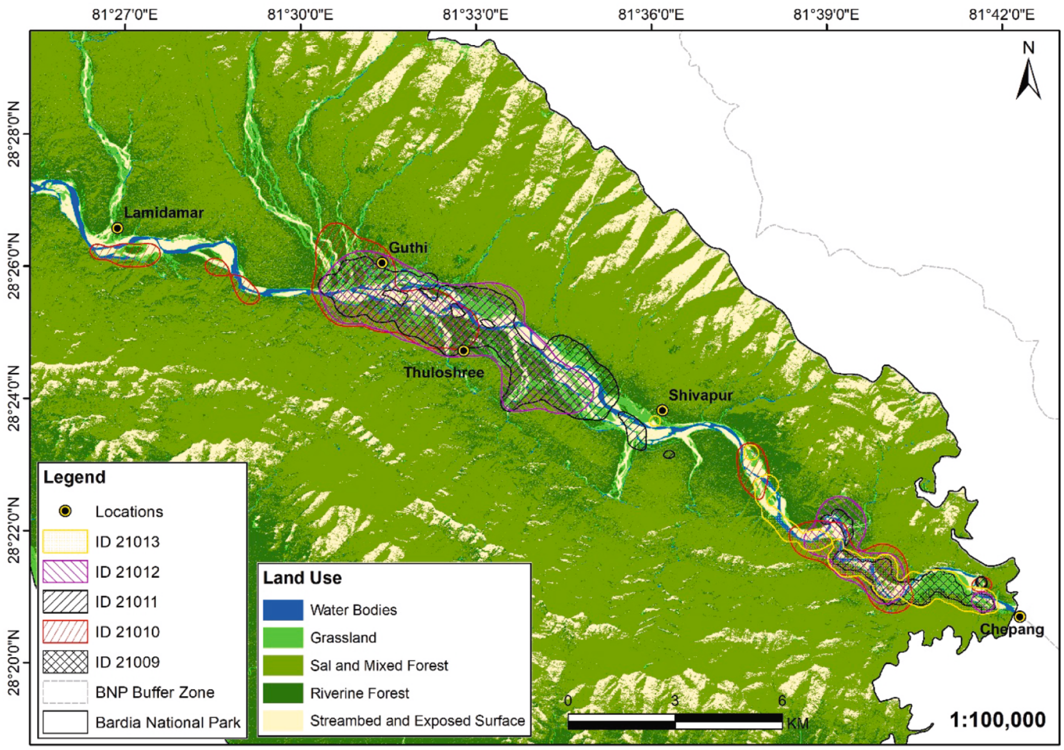

Table 2. Overall and seasonal home ranges of individual rhinos in Babai Valley inside Bardia NP.

Fig. 2. Overall, the Kernel home range of five radio-collared rhinos is shown on the land cover map of the study area.

release behavior, showing that rhinos used larger home ranges compared to Chitwan NP, primarily due to low graded habitat quality, limited grassland, fragmented riverine forests, and seasonal scarcity of water and forage. Grassland was the most preferred habitat, while *S. robusta* and mixed forests were the least used. Female rhinos' home-range size and movement patterns may be influenced by reproductive status and resource availability. One female may have been pregnant, while the other appeared to be seeking resources, which could explain the wide variation observed in their home ranges. Habitat degradation from floods further reduced suitability, forcing rhinos to range widely. Given the small population size and fragmented habitat, Babai Valley may not support a viable rhino population without significant habitat restoration, addition of individuals, or relocation to more suitable sites. Effective management—such as grassland restoration, waterhole maintenance, and strengthened anti-poaching measures—is found critical for ensuring the long-term success of rhino reintroduction efforts in Nepal.

Translocation for conserving rare and threatened wildlife species is a common practice, but studies on post-release monitoring remain limited (Dutta et al., 2017). Our study on translocated rhinos in the Babai Valley of Bardia National Park provides important insights for their management, especially forage and grassland dynamics, water availability, and floodplain use, habitat connectivity, and spatial planning. Although conducted over a short period (3–11 months), fine-scale data obtained via satellite radio collars were analyzed using a robust framework based on individual utilization distributions to estimate home ranges. We also applied the traditional MCP method to enable comparisons with past studies (Subedi et al., 2013).

4.1. Home range of male and female rhinos

The kernel density home range of reintroduced rhinos in Babai Valley ranged from 3.15 km^2 (ID 21009) to 19.45 km^2 (ID 21012). The

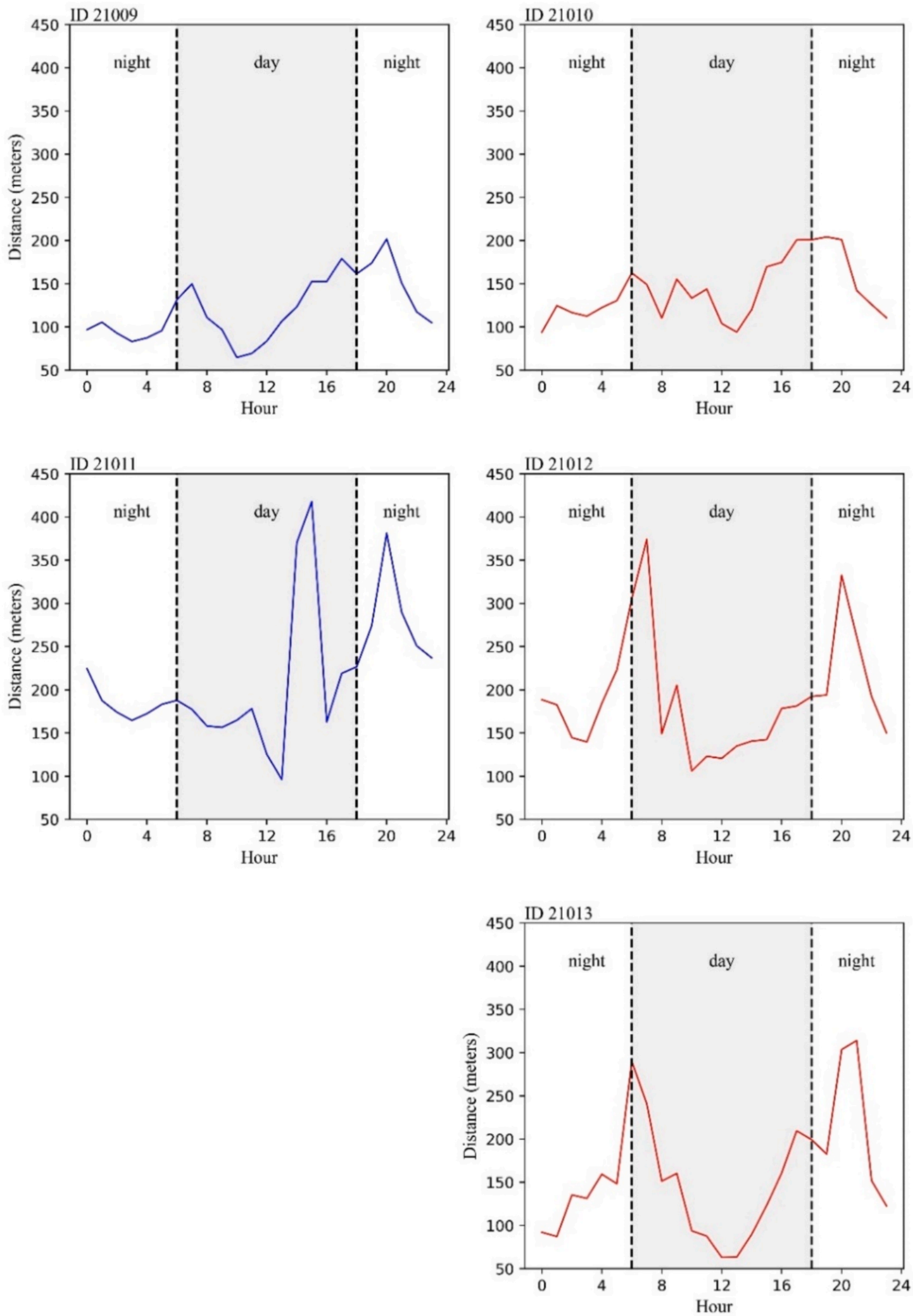

Fig. 3. Movement patterns of reintroduced rhinos in Babai Valley. Hours are shown in 24-hour format on the x-axis and distance travelled in meters on the y-axis.

adult male rhino (ID 21009) had the smallest home range, likely due to its old age and illness. This individual died approximately eleven months after translocation due to lung and liver failure based on necropsy. Field monitoring by the park authority reported that the male rhino spent most of its time in the Chepang Phanta Area in the Eastern part of Babai Valley. In contrast, the adult female rhinoceros (ID 21012) with the largest home range was pregnant during reintroduction and gave birth to a calf two months later, likely traveling across a long distance to find a safe and favorable site for parturition.

A similar study using VHF radio collars to track reintroduced rhinos in the Karnali floodplain area of Bardia National Park in the 1990 s reported an average annual home range of 28.5 km^2 (Subedi et al., 2013; Talukdar et al., 2025). While our estimates based on Karnel density estimators were smaller, a similar method used in a previous study, was

Table 3
Overall, seasonal and day/night movement patterns of reintroduced one-horned rhinos in Babai Valley. Daytime is defined as 06:00–17:59 and nighttime as 18:00–23:59 and 00:00–05:59, Nepal Standard Time (NST).

Rhino ID	Distance covered (km)	Days	Mean daily movement (km)			Mean day-night movement (km)			
			Overall	Hot dry season	Monsoon season	Day time	Daytime per hour	Nighttime	Nighttime per hour
21,009	895.619	329	2.714 ± 0.124	2.533 ± 0.284	3.25 ± 0.154	1.332 ± 0.075	0.111	1.382 ± 0.083	0.115
21,010	937.426	162	2.841 ± 0.205	3.972 ± 0.521	2.357 ± 0.208	1.587 ± 0.238	0.132	1.557 ± 0.196	0.130
21,011	897.42	206	4.335 ± 0.296	4.487 ± 0.411	4.182 ± 0.425	1.749 ± 0.147	0.146	2.587 ± 0.218	0.216
21,012	900.531	208	4.288 ± 0.251	4.821 ± 0.427	3.775 ± 0.235	1.935 ± 0.153	0.161	2.363 ± 0.184	0.197
21,013	520.46	139	3.718 ± 0.267	4.069 ± 0.450	3.395 ± 0.286	1.710 ± 0.161	0.142	2.008 ± 0.195	0.167

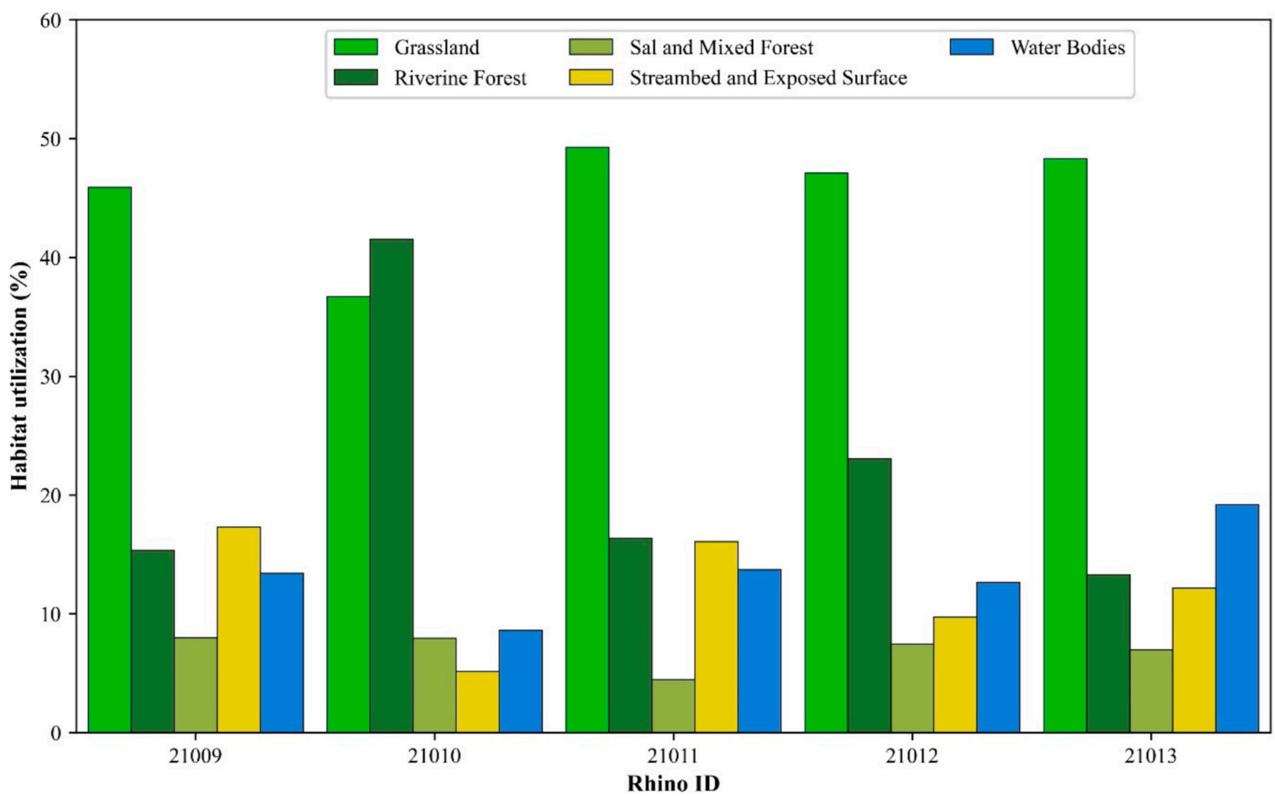

Fig. 4. Graphical presentation of the habitat used by reintroduced rhinos in Babai Valley.

Table 4
Different habitats used by reintroduced rhinos in Babai Valley.

Land Cover	Rhino ID					Overall
	21,009	21,010	21,011	21,012	21,013	Mean
Grassland	45.91	36.71	49.29	47.11	48.33	45.47
Riverine Forest	15.36	41.54	16.39	23.06	13.29	21.93
Sal and Mixed Forest	7.99	7.96	4.49	7.46	6.99	6.98
Streambed and Exposed Surface	17.32	5.17	16.09	9.73	12.17	12.10
Water Bodies	13.42	8.62	13.74	12.63	19.22	13.53
Total	100.00	100.00	100.00	100.00	100.00	

comparable (32.89 km^2). Both studies indicate larger home ranges in Bardia compared to Chitwan. Subedi (2013) suggested that non-settled ranging behavior, low population density, and limited availability of suitable habitats – the alluvial floodplain grasslands dominated by *Saccharum spontaneum* could drive these larger home ranges (Subedi et al., 2013). Our findings support this conclusion, suggesting that rhinos in Babai Valley may still be exploring their new suitable environment (habitats) and searching for mates (Fig. 5).

We observed irregular home range patterns in both females and males (Fig. 5), contrasting with Jnawali (1995), who reported average annual home ranges of 41.8 ± 4.4 km^2 for males and 25.1 ± 9.3 km^2 for females in the Karnali floodplain population (Jnawali, 1995; Subedi et al., 2013). Subedi (2013) reported in Chitwan National Park that the average annual 95% Kernel home ranges were 20.54 ± 6.06 km^2 for males and 10.58 ± 1.34 km^2 for females. Studies of white rhinos in Hluhluwe-Imfolozi Game Reserve, South Africa, also found that females have larger, overlapping home ranges, whereas males are more territorial and restrict their ranges to exclude other dominant males. Females may traverse larger areas not only for feeding but also to encounter multiple males for mating opportunities (White et al., 2007).

Table 5
Seasonal habitat use of reintroduced one-horned rhinos in Babai Valley.

Land Cover	Rhino ID					Overall
	21,009	21,010	21,011	21,012	21,013	Mean
Hod-dry season						
Grassland	37.69	37.35	47.86	36.98	36.55	39.29
Riverine and Mix Forest	18.69	38.08	11.18	24.43	13.93	21.26
Sal and Other Forest	9.80	6.18	3.17	9.53	5.24	6.78
Streambed and Exposed Surface	17.19	6.47	19.80	9.82	13.23	13.30
Water Bodies	16.63	11.92	17.97	19.23	31.05	19.36
Monsoon season						
Grassland	58.05	35.28	50.87	56.76	58.86	51.96
Riverine and Mix Forest	10.80	48.69	22.31	21.76	12.71	23.25
Sal and Other Forest	6.71	11.79	5.97	5.49	8.55	7.70
Streambed and Exposed Surface	13.55	2.46	11.89	9.64	11.23	9.75
Water Bodies	10.90	1.78	8.95	6.35	8.66	7.33

4.2. Habitat use and quality for rhinos

We observed that the floodplain grasslands in Babai Valley occur as small, unevenly distributed patches along both banks of the East-West before turning to the South. This narrow floodplain (average width 1.1 km) adjoins the Siwalik Hills, creating a suboptimal habitat for rhinos. Field observations indicated that individual patches of suitable habitat are likely too small to provide sufficient high-quality forage throughout the year to support breeding and colonization of the reintroduced rhinos. Consequently, rhinos must move between patches to meet their dietary needs.

Larger home ranges of reintroduced rhinos in Babai compared to their source population of Chitwan NP indicate a low graded habitat quality. In Chitwan, soil moisture in tall grasslands remains 20–30% year-round, allowing palatable riverine flora to intermingle with grasses (Subedi et al., 2013). In contrast, the Babai floodplain consists of young and shallow alluvial sandy soils over a thick layer of boulders, where moisture drops below 5% during the dry season (Lehmkuhl, 1994; Pant et al., 2022). This aridity limits the growth of grass and herbaceous plants except during the monsoon. As a result, rhinos in Babai Valley must travel farther in the hot, dry season to access forage, especially browsing species like *Litsea monopetala, Dalbergia sissoo,* and *Trewia nudiflora*, as the sprouting of *Saccharum spontaneum* is limited (Steinheim et al., 2005; Thakur et al., 2025).

Catastrophic floods in the Babai River in 2015 and 2017 further degraded habitat quality, washing the grasslands and depositing large boulders, gravel, and sand across large parts of floodplain habitats. Many artificial waterholes created to target the reintroduced rhinos were destroyed, forcing rhinos to travel longer distances to meet their biological requirements. Riverine forests, another preferred habitat, are also fragmented and scattered in small patches, causing rhinos to cover larger areas, especially during the dry season. Artificial water holes also dry up often, forcing rhinos to move long distances for wallowing. In the monsoon, with abundant floodplain grasses and wallows, rhinos do not need to travel to larger areas. In Chitwan, continuous blocks of riverine forest, including *Khair-Sissoo, Trewia nudiflora, Litsea monopetala,* and *Mallotus philippinensis*, are abundant, but in Babai Valley, these forests are sparse and fragmented, likely resulting in less utilization of riverine habitats (Subedi et al., 2013).

4.3. Daily movement of the rhinos

The average daily distance traveled by female rhinos was slightly higher than that of males. A study by Subedi (2013) (Subedi et al., 2013) in Chitwan NP, it was found that males traveled longer distances (>6 km/day) than females (≈4 km/day), consistent with earlier findings by Dinerstein (1992). In Babai Valley, most individual rhinos traveled more at night, except for one female (ID 21010), who may have limited nighttime movement to protect her small calf. Human disturbance in Babai Valley is minimal at present, although the area came under protection after displacing the historic human settlement for ecological benefits (Pandey et al., 2024, Pandey et al., 2025a), which is mainly limited to occasional patrolling and research activities as observed. Previous studies suggest that rhinos move more at night due to reduced predation risk, lower human disturbance, and milder temperatures, especially during the hot-dry and monsoon seasons. Daytime temperatures often exceed 35 °C, limiting foraging in open grasslands and prompting rhinos to wallow or rest in riverine forests.

During the hot-dry season, rhinos used water bodies and streamed/exposed surfaces more than during the monsoon (19.36% vs. 7.32%), likely due to sedimentation caused by the 2017 flash floods, which covered previous habitats with boulders and sand. Grasslands were highly preferred in both seasons, with species such as *Saccharum spontaneum*, *Saccharum bengalensis*, *Arundo donax*, and *Erianthus ravennae* comprising ~ 70% of the diet in the monsoon (Lehmkuhl, 1994; Pant et al., 2022; Subedi et al., 2013). Tall grasslands were also used after the first rains in the hot season. The narrow floodplain, bordered by the Siwalik Hills, restricts movement and limits distinct habitat mosaics, resulting in prolonged use of grasslands. Waterholes and oxbow lakes are critical for wallowing; permanent water sources exist mainly in the Guthi Area, with additional artificial waterholes in Babiyachaur and Thuloshree grasslands supplied via solar pumps. The Babai River and tributaries also provide water resources to the wildlife, including rhinos. *S. robusta* and mixed forests were seldom used due to limited food resources, though some usage of *Imperata cylindrica* in *S. robusta* forests occurred during early sprouting stages, as observed for rhinos ID 21011 and ID 21012.

4.4. Conservation implications and limitations of the study

Reintroduction can be an effective conservation tool when guided by scientifically informed strategies and risk assessments (Taylor et al., 2017). The Government of Nepal has made multiple efforts to reintroduce rhinos into the Babai Valley of Bardia National Park, part of their historical range. Although reintroduced rhinos survived and successfully gave birth to calves, long-distance movements indicating unsettled behavior in the new environment, low population density, and limited availability of suitable habitats are likely caused by the larger home range size in Bardia NP compared to their source population (Chitwan NP). Thus, targeted habitat restoration is essential, including expansion and connectivity of grasslands and riverine forests, rehabilitation of floodplain areas covered by boulders and sedimentation, and maintenance of artificial waterholes with year-round water availability for wallowing. Management strategies should prioritize the habitat restoration interventions, particularly for the hot-dry period when forage scarcity and water limitations are critical. Human disturbance, although currently minimal, should be continuously monitored and mitigated to prevent stress-induced alterations in movement patterns and avoid poaching. Continued post-release monitoring using GPS collars and field surveys is necessary to track home range dynamics, habitat preferences, and reproductive success over longer periods. Additionally, reinforcing the population with individuals of diverse age and sex classes can enhance breeding opportunities and long-term viability, while further studies on food availability, nutritional quality, and flood impacts will strengthen habitat management decisions to meet the local needs (DNPWC, 2022; GoN, 2016, 1973; Pandey et al., 2025c, Pandey et al., 2025b) and global goals such as the Biodiversity 2030 Framework (CBD, 2022), Sustainable Development Goals (UN, 2015) and beyond.

However, small and isolated groups cannot ensure long-term survival, highlighting the need for a quantitative assessment of habitat

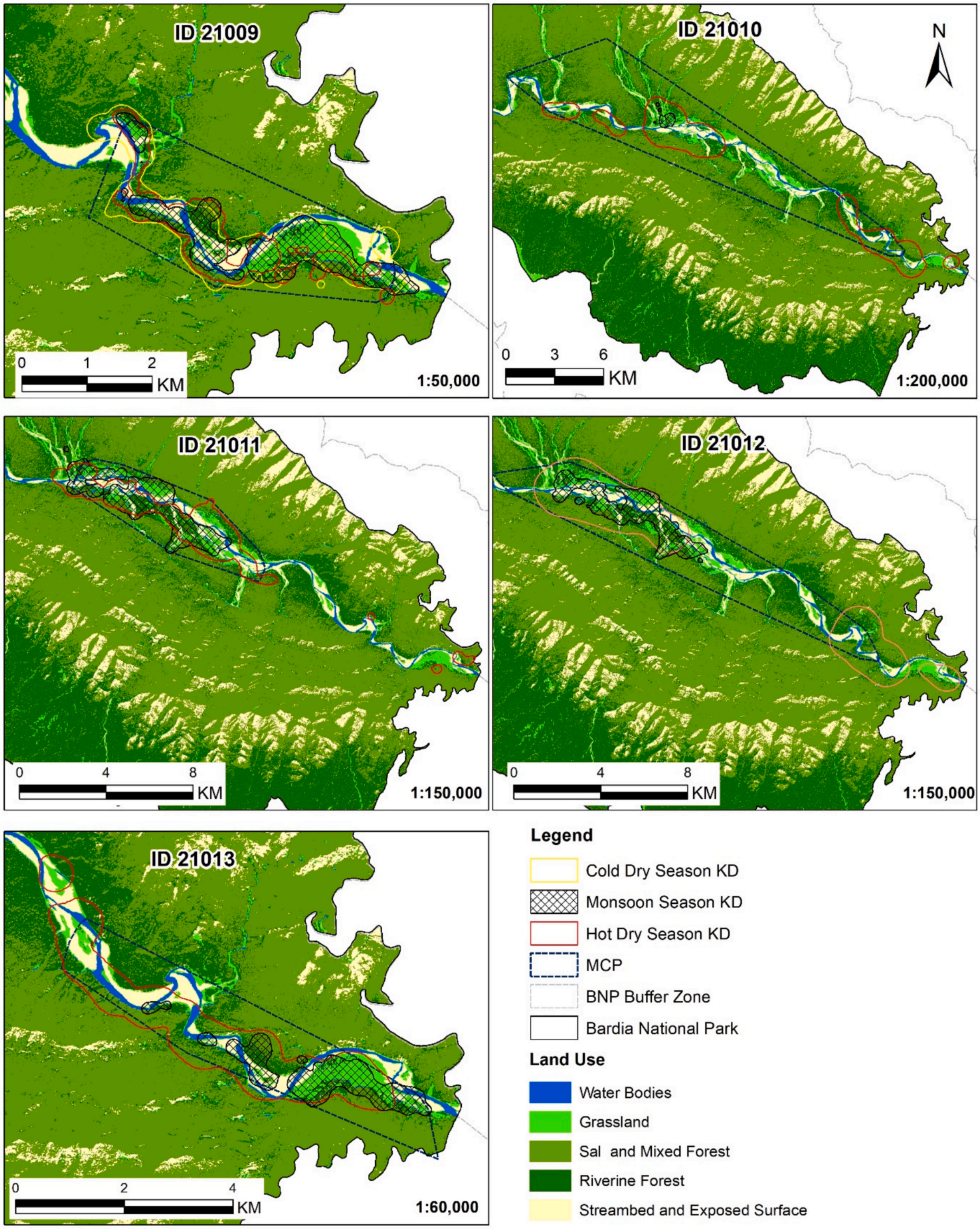

Fig. 5. Home range distribution and habitat use of individual reintroduced rhinos in Babai Valley. KD in the legend stands for Kernel Density, and MCP stands for Minimum Convex Polygon.

quality and population viability. Supplementing the population with additional rhinos or relocating individuals to more suitable habitats, alongside habitat restoration, grassland management, and enhanced water availability, is essential for ensuring population sustainability. Security and anti-poaching measures could also be intensified in key habitats that play a vital role in rhino conservation and habitat integrity. Future conservation policy, especially for mega herbivores and pachyderms like rhinos, should be embedded within an adaptive habitat mosaic framework that integrates grassland restoration, riverine forest management, and engineered floodplain features to buffer seasonal habitat loss. Moreover, incorporating floodplain engineering measures—such as stabilizing riverbanks, managing sediment dynamics, and maintaining perennial water sources—can enhance habitat resilience, reduce post-release dispersal stress, and improve long-term population viability across translocation landscapes.

A key limitation of this study is its relatively short monitoring period of 11 months and the small sample size of only five radio-collared rhinos. These constraints limit the ability to generalize findings to the entire reintroduced population and to fully assess long-term home range dynamics, seasonal movement patterns, reproductive success, and survival rates. Moreover, habitat use may have been influenced by the initial post-release adjustment period, which could differ from long-term behavioral patterns. Future studies with larger sample sizes, longer monitoring periods, and consideration of additional ecological variables—such as forage quality, predation risk, and human disturbance—would provide a more comprehensive understanding of the reintroduced rhinos' ecology and conservation needs.

5. Conclusion

Reintroduction guided by scientific strategies and risk assessments remains an effective conservation tool. In Bardia National Park of Nepal, translocated one-horned rhinos exhibited larger and more irregular home ranges than previously reported, likely due to fragmented habitats, seasonal floods, and environmental constraints. Grasslands were consistently preferred, while riverine and forested areas were less used, and nocturnal activity predominated, reflecting behavioral adaptation to resource availability. The small, isolated population suggests the need for quantitative habitat and population assessments, supplemented by translocations, habitat restoration, grassland management, and enhanced water availability. Along with these measures, strengthening security and anti-poaching measures, participatory management, and a community stewardship approach could be key strategies in sustaining rhinos' population in the new environment, as observed in Bardia National Park of Nepal. In gist, our results suggest critical insights on forage, water, connectivity, and space-related assurance, which are fundamental for biological conservation, including for the rhinos. These findings inform Nepal's national rhino metapopulation strategy, support evidence-based management of post-translocation populations, and offer practical guidance for future reintroductions in historically occupied but under-utilized habitats.

CRediT authorship contribution statement

Rishi Ranabhat: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Hari Prasad Pandey:** Writing – review & editing, Supervision, Correspondence. **Shravan Kumar Ghimire:** Software, Methodology, Writing – review & editing. **Naresh Subedi:** Writing – review & editing, Supervision. **Babu Ram Lamichhane:** Software, Methodology, Writing – review & editing. **Khim Bahadur KC:** Data collection, Methodology, Writing – review & editing. **Tek Narayan Maraseni:** Supervision, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2026.127302.

Data availability

Data ownership: GPS telemetry data are the property of the Department of National Parks and Wildlife Conservation (DNPWC), Government of Nepal.

Authorization: Data access was granted under an official research permit and institutional authorization issued by DNPWC for post-translocation monitoring in Bardia National Park. This authorization governed data use prior to manuscript submission.

Public availability: The telemetry data were not publicly available, consistent with Nepal's policy on sensitive wildlife data. This has now been explicitly stated.

Non-sensitive data: All non-sensitive ecological datasets (Sentinel-2 imagery, classified habitat rasters, accuracy assessment outputs, movement summaries) are publicly available (Sentinel-2) and also available upon reasonable request through DNPWC or the corresponding author, without compromising rhino security. We have now provided the spatial analysis data in the supplementary file (S1).

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