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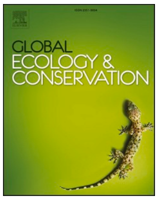

Ecological factors associated with hispid hare (Caprolagus hispidus) habitat use and conservation threats in the Terai Arc Landscape of Nepal

Bijaya Dhami [a,b], Bijaya Neupane [c,d], Nishan K.C. [c], Tek Maraseni [e], Chitra Rekha Basyal [c], Laxmi Raj Joshi [f], Hari Adhikari [g,*]

[a] Department of Biological Sciences, University of Alberta, AB 116 St & 85 Ave, Edmonton, Canada
[b] IUCN/SSC Deer Specialist Group, 1196 Gland, Switzerland
[c] Institute of Forestry Pokhara Campus, Tribhuvan University, Pokhara 33700, Nepal
[d] Department of Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, 00014, Finland
[e] University of Southern Queensland, Toowoomba, Queensland 4350, Australia
[f] National Trust for Nature Conservation, Kanchanpur 56400, Nepal
[g] Earth Change Observation Laboratory, Department of Geosciences and Geography, University of Helsinki, P.O. Box 68, FI-00014 Helsinki, Finland

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ABSTRACT

The hispid hare (Caprolagus hispidus) is one of the most elusive mammals and is listed as an endangered species both globally by the International Union for Conservation of Nature (IUCN) and nationally by National Red list series, Nepal. The species is experiencing a continuous decline across its distribution range due to increasing anthropogenic activities in its habitats. Limited information on the species distribution and the factors affecting its habitat use have restricted site-specific conservation actions. In this study, we aim to identify the current distribution pattern, factors associated with the habitat use of the hispid hare, and prevalent conservation threats in Shuklaphanta National Park (ShNP) of Nepal. We conducted a strip transect-based survey in January and February 2021 across 12 sampling grids of 0.5 km × 0.5 km. The presence of hispid hare was assigned to 1 if any indirect sign of its presence was observed "used plots," otherwise to 0 if any indirect sign of its presence was not observed ("habitat availability plot"). We next measured six habitat predictors (i.e., nearest distance to a water source, ground cover, ground condition, habitat type, dominant plant species, and presence/absence of anthropogenic disturbance) from both types of plots ("used" and "habitat availability plot"). We found that the overall distribution of hispid hare was clumped. Confirming a new distribution location around the Baba Tal area in ShNP will alert conservation managers to the need of a rapid assessment of its presence–absence across the lowlands of Nepal. Except for the nearest distance to a water source, all other five habitat factors influenced the probability of encountering a hispid hare. Out of six threats, four threats (i.e., grassland burning during the breeding season, grassland succession, habitat loss and fragmentation, and thatch collection from woodland) were determined as the most severe for the hispid hare. Our findings will enable park managers and local government to formulate and plan suitable conservation measures to protect this threatened and endangered species and its habitats. In addition, our results will act as a baseline for further research in ShNP and other similar regions.

* Corresponding author.
E-mail address: hari.adhikari@helsinki.fi (H. Adhikari).

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1. Introduction

The order Lagomorpha includes small and medium-sized mammals, such as pikas and rabbits, which are members of the Ochotonidae and Leporidae families. Except for Antarctica, all continents are known to be home to these mammalian species (Chapman and Flux, 2008). Nepal hosts two sympatric species of hare (the hispid hare and the india hare). The hispid hare (*Caprolagus hispidus*) is the world's rarest mammal with a monotopic genus (Tandan and Dhakal, 2013). Globally, the hispid hare is listed as endangered in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Aryal and Yadav, 2019) and under Appendix I of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES, 2021). In Nepal, the hispid hare is categorized as a protected priority species under the National Park and Wildlife Conservation Act, 1973 (GoN, 1973) and is also listed as an endangered species in the National Red list series (Yadav et al., 2008; Jnawali et al., 2011). Additionally, it is one of the lagomorph species listed by the US Endangered Species Act (Nath, 2015).

Historically, the hispid hare was distributed in the southern Himalayan foothills from Uttar Pradesh (India) through Nepal and West Bengal to Assam (Maheswaran, 2006). During the mid-1960s, ecologists speculated that the hispid hare had become extinct; however, the live capture of a specimen in 1971 from Bornadi Wildlife Sanctuary, Assam, confirmed its presence. It currently has a patchy distribution in southern Asia, including the countries of Nepal, Bhutan, Bangladesh, and India (Nath and Machary, 2015; Khadka et al., 2017) within an elevation range of 100–250 m (Aryal and Yadav, 2019). In Nepal, studies have reported hispid hares in the isolated pocket areas of Shuklaphanta National Park (ShNP), Bardia National Park (BNP), and Chitwan National Park (CNP) (Khadka et al., 2017).

The hispid hare principally prefers tall grasslands with early-succession vegetation adjacent to riverbanks (Bell et al., 1990). In Nepal, its significant habitats are the floodplain grasslands of the Terai (lowland) region, which are distinct from other typical dry and scrub grasslands found throughout the subcontinent (Aryal and Yadav, 2019; Sadadev et al., 2021). The floodplain or alluvial grasslands consist of tall grass species, including *Saccharum spontaneum*, *Imperata cylindrical*, *Desmostachya bipinnata*, *Narenga porphyrocoma*, and *Themeda arundinacea* (Aryal et al., 2012; Khadka et al., 2017; Sadadev et al., 2021). The hispid hare mostly prefers thatch shoots and roots, which they bite off at the base and strip off the outer sheaths before consumption (Oliver, 1980). Though the grasslands of the Terai floodplain are crucial for Nepal's biodiversity protection and local inhabitants by providing fuel and thatch

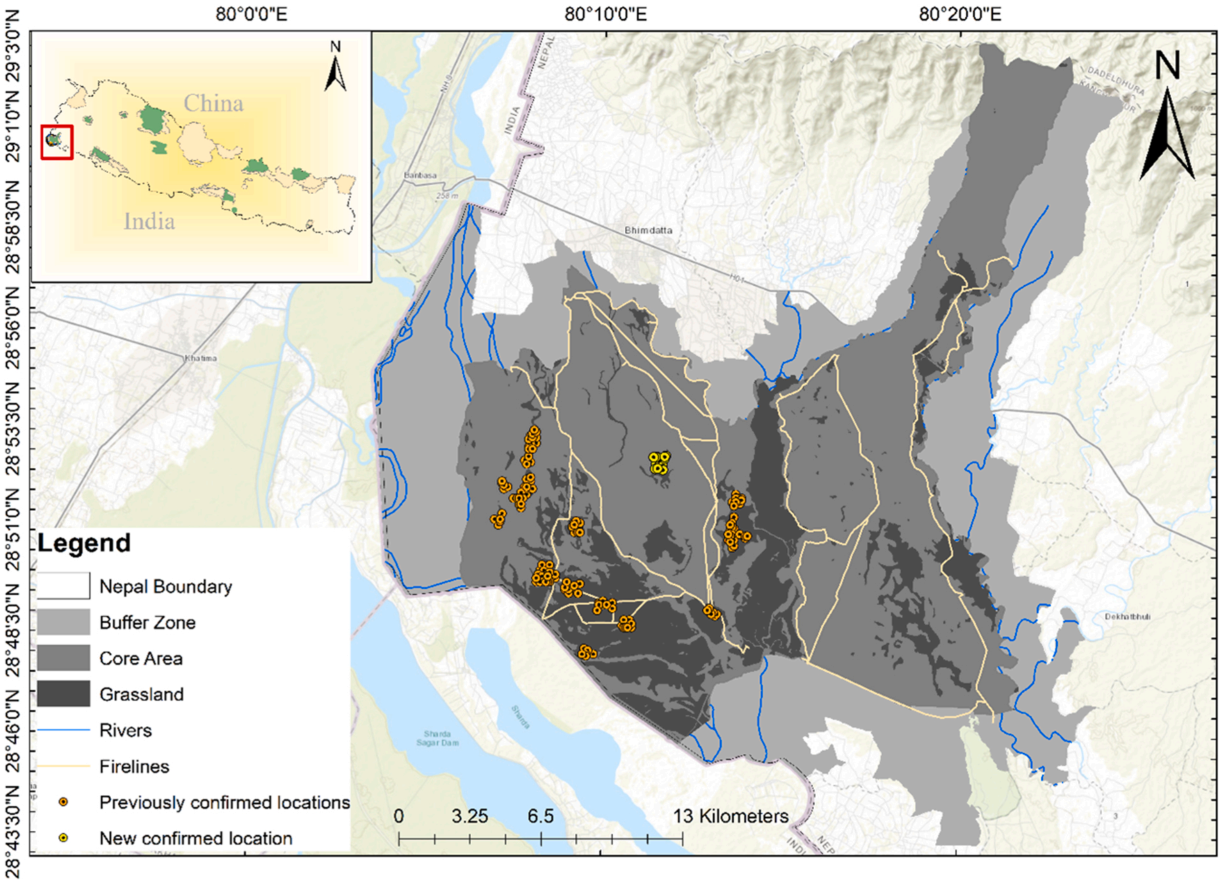

Fig. 1. Map of Shuklaphanta National Park showing the distribution of hispid hares, where yellow circles indicate a newly confirmed distribution location of the species, i.e., from the Baba Tal area, and orange circles indicates previously confirmed locations of the species.

roofing (Bhatta, 1999), these areas are threatened, mainly due to natural succession, overgrazing of cattle, unregulated thatch collection, and uncontrolled burning (Yadav et al., 2008; Jnawali et al., 2011). Consequently, a tiny habitat refuge is left on these grasslands for small mammals, including hispid hares (Chand et al., 2017).

The ecological study and inventory of small mammals in the Indian subcontinent's grasslands are limited compared to large mammals (Aryal et al., 2012; Tandan and Dhakal, 2013; Nidup, 2018). Similarly, Nepal's Lagomorpha is an under-researched mammalian order (Bist et al., 2021). Globally, several studies have investigated the hispid hare, focusing on multiple themes, including habitat preferences and population density (Nath and Machary, 2015); camera trapping (Nidup, 2018); behavioral ecology, home range, and potential threats (Bell, 1987); the impact of grassland burning (Sadadev et al., 2021); diet (Aryal et al., 2012); and habitat use (Aryal et al., 2012; Chand et al., 2017). However, to date, no comprehensive study has been conducted systematically to assess the ecological and anthropogenic factors influencing the hispid hare's habitat selection across its range. Chapman and Flux (1990) suggested that this species should be captively bred; however, a prior captive breeding program attempted in 1987 failed (Bell, 1987). Information on ecological and anthropogenic factors influencing the habitat use of threatened species has been identified as a crucial component that aids in designing targeted conservation measures for their habitats (Calenge, 2007; Raha and Hussain, 2016).

Factors including distance from human settlement, distance from a water source, ground cover, ground condition, dominant vegetation, habitat type, and anthropogenic disturbance are likely to influence the habitat selection of hispid hares (Aryal et al., 2012; Maheswaran, 2006, 2002; Yadav, 2006; Yadav et al., 2008; Nath et al., 2010; Tandan et al., 2013; Nath and Machary, 2015; Chand et al., 2017; Khadka et al., 2017; Nidup, 2018; Sadadev et al., 2021). These factors may impact their distribution and resource requirements (Klaassen and Broekhuis, 2018). Therefore, our study aims to bridge this existing knowledge gap and assess the factors associated with the presence or absence of the hispid hare in ShNP, a major hispid hare pocket area in Nepal (Sadadev et al., 2021). Furthermore, we aim to identify the prevalent conservation threats to hispid hares in the study area. The findings of this study will inform conservation managers and the government to plan and implement both urgent and long-term conservation efforts that will help to maintain a viable population of the species. We expect our findings to act as a baseline for detailed research in ShNP and elsewhere.

2. Materials and method

2.1. Study area

ShNP is one of the lowland protected areas of Nepal situated in the southwestern part of Kanchanpur District (latitude 28°49'–28°57'N and longitude 80°07'–80°15'E) (Fig. 1). It was declared a wildlife reserve in 1976 and upgraded to a national park in 2017 (Sadadev et al., 2021). It covers a total area of 305 km^2, 16.1 % of which comprises grassland (Aryal et al., 2012). The Mahakali River borders the park in the west, Lagga Bagga, an Indian national forest in the south, and the protection forest of the Kanchanpur District in the east and north. The region has a subtropical monsoon climate, with a mean annual rainfall of 1579 mm, most of which falls from June to September, with August as the peak rainfall month. December and January are colder months, with daytime highs of 7–12 °C (45–54 °F) and sporadic frost, mainly in the morning and night. The temperature increases from the beginning of February, reaching up to 25 °C (77 °F) in March and 42 °C (108 °F) by the end of April (Chand et al., 2017). The ShNP inhabits 665 plant species from 438 genera and 118 families, the highest diversity documented among protected areas in the Terai region of Nepal. The park is also rich in faunal diversity and supports 57 mammalian species (Poudyal et al., 2020) and 71 species of herpetofauna (Rawat et al., 2020).

2.2. Data collection

Seven key informant interviews were initially carried out in January 2021 with representative staff (game scouts) from the ShNP (n = 2), the National Trust for Nature Conservation (n = 2), the Buffer zone management committee (n = 1), and the nature guide association (n = 2) to identify probable and potential locations for the hispid hare. These selected key informants had first-hand experience working with the species in the past. During the interviews, the interviewer provided a well-illustrated historical distribution map (color printed) of the species to facilitate the respondents in precisely identifying current and probable distribution locations. Based on their knowledge and experiences of the study site, they also listed existing threats that have affected the hispid hare population and the habitat. The research team then carried out a preliminary field visit. GPS coordinates of probable and potential locations marked by the key informants were surveyed in the field with the help of field-experienced game scouts and nature guides. The recorded coordinates were plotted in the latest version of ArcGIS 10.8 to ensure that a grid of 0.5 km × 0.5 km could be laid out at selected probable hispid hare locations.

The detailed field visit was carried out during the cold winter season (18–28 February 2021) because of the sparser vegetation cover in tropical regions during this season (Safford, 2004; Sanusi et al., 2013; Neupane et al., 2022). The sparser vegetation cover in winter increases the probability of detecting hispid hare pellets, preventing bias caused by un-detectability (Sadadev et al., 2021; Dhami et al., 2023). Identification of the species is a crucial step in many ecological studies. Non-invasive molecular methods are more convincing evidence of species presence (Buglione et al., 2020a, 2020b); however, the shape and size of pellets are also regarded as precise evidence for species confirmation (Aryal et al., 2012; Sadadev et al., 2021). Hispid hare pellets were differentiated from rufous-tailed Indian hare (*Lepus nigricollis ruficaudatus*) pellets by their larger size and flattened and rounded shape, whereas Indian hare pellets are smaller, often darker and elliptical with a pointed end (Oliver, 1985; Yadav, 2006; Yadav et al., 2008; Aryal et al., 2012; Chand et al., 2017; Sadadev et al., 2021). The knowledge that experienced field assistants (game scouts and guides) possess concerning pellet identification was verified and further enhanced by providing printed color photos of pellets excreted by similar herbivore species found in the study area.

We employed an occupancy sampling strategy for our detailed field survey that requires surveying species of interest at a reasonable geographic scale for both detection and non-detection, to simulate the link between species and habitat (MacKenzie et al., 2002). The size of a sampling unit should generally exceed the extent of a species' expected home range to sustain the assumption of geographic closure and independent sample locations (MacKenzie et al., 2002). A male hispid hare's home range is 2034 m^2 (night) and 428 m^2 (day), whereas a female's is 242 m^2 (night) and 77 m^2 (day) (Bell, 1987). As our study aimed to evaluate the impact of several habitat predictors on hispid hare habitat usage rather than actual occupancy per se, a grid of 0.5 km^2 was overlaid in the study area as a sampling unit. Based on information collected through the key informant interviews and the preliminary filed survey, we randomly selected 12 grids inside the core area of the ShNP for detailed sampling. These selected grids included previously confirmed locations of the species (8 grids) and locations with potential distributions (4 grids) [locations having similar habitat conditions as those of previously confirmed locations]. We also ensured that these 12 selected grids represented different habitat types used by the hispid hare, as mentioned by Chand et al. (2017). In each chosen grid, two main transect lines 500 m in length were laid and spaced at 200 m to minimize the possible overlapping of pellets. In each main transect, an alternate strip transects 20 m in length and 2 m in width (Sadadev et al., 2021) was laid out in an equally spaced manner of 100 m (Fig. 2). The research team members (first author and two experienced field guides who had first-hand experience in ecological assessment of the hispid hare) intensively searched for indirect signs of hispid hare (pellets, grass cuttings, dens) presence along the systematically positioned transect lines, as the direct sighting of such nocturnal and elusive species is difficult. (Bell, 1987; Bell et al., 1990). Whenever indirect signs were observed, a 1.78 m radius circle was set up, with the detected signs in the center (Gyawali, 2003). From the center of each sign-detected circle, the research team moved 100 m in a random direction and set up another circle of the same size (Khulal et al., 2021; Neupane et al., 2021, 2022). These circle plots represented typical habitat samples, regardless of the presence or absence of hispid hare. If any evidence of hispid hare presence was found in any of these circles, it was assigned a value of 1 ("used plots"), otherwise a value of 0 ("habitat availability plot") was assigned.

Based on the preliminary field survey and review of available literature (Bhatta, 1999; Maheswaran, 2002; Yadav et al., 2008; Nath et al., 2010; Aryal et al., 2012; Tandan et al., 2013; Nath, 2015; Nath and Machary, 2015; Nidup, 2018), we recorded six predictor variables with potential influence on hispid hare habitat uses in all circles of both types ("used plots" and "availability plots") (Table 1). Firstly, the shapefile of the water source was extracted from a digital elevation model (DEM, 12.5-m resolution) and from Landsat Image 8 (USGS, 2021). We then calculated the distance to the nearest water source using the "Nearer function" in ArcGIS 10.8 with the presence locations (geographic coordinates) of the hispid hare. Habitat type was determined based on direct observations (Khulal et al., 2021; Neupane et al., 2021). Similarly, ground cover was visually estimated using a circular bamboo frame (radius 1.78 m)

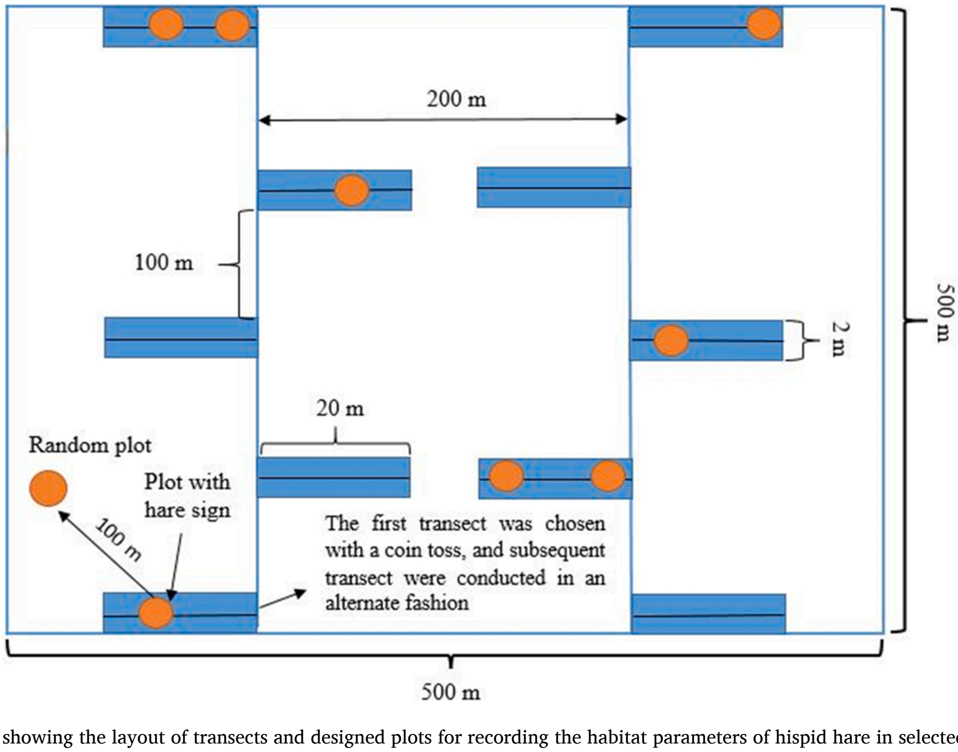

Fig. 2. Diagram showing the layout of transects and designed plots for recording the habitat parameters of hispid hare in selected sampling units. The alternately placed blue rectangular boxes represent strip transects and the orange circles represent sampling plots ("Availability plots" or "used plots") where various habitat parameters were recorded. The first transect was chosen with a coin toss, and subsequent transect were conducted in an alternate fashion.

bisected with two diagonal sticks (Roshetko et al., 2002). We estimated the total grass species coverage percentage based on the sum of the proportion coverage in each quadrant within the circular frame. The ground condition was determined based on the presence/absence of moisture in the soil, while the dominant plant species were identified based on the highest percentage coverage of species recorded from the circle. And finally, the presence/absence of anthropogenic disturbance was based on direct observation and coded as "1" for presence and "0" for absence (Table 1).

To assess the conservation threats to hispid hares in ShNP, we additionally adopted three approaches (direct field visit, systematic literature review, and focal group discussion (FGD)). During the detailed field survey, we identified and recorded the conservation threats impending the survival of hispid hares in the national park. Further, the first author performed a systematic review of the literatures across Nepal concerning the conservation threats to hispid hares following the method adopted by Dhami et al. (2021). The first FGD (n = 7) was carried out with representatives from the national park (n = 2), National Trust for Nature Conservation (n = 2), the buffer zone management committee (n = 1), the nature guide association (n = 1), and local biologists (n = 1). The first FGD aimed to identify, list, and select the major conservation threats. During this phase, participants were asked to list the major conservation threats to hispid hares in ShNP based on their field-based knowledge and experiences. Through this approach, nine major threats were identified and listed (Fig. 3), and these were subsequently ranked during the second FGD phase using the relative threat ranking method (WWF, 2007; Chhetri et al., 2020; Khulal et al., 2021). We next provided each participant (7 members) of the FGD with a printed list of the nine major threats and requested them to rate each threat in relation to their effect on the hispid hare in ShNP. Each threat type could be scored from 1 to 10. Later, all the scores received from the participants were averaged for each threat (Nishan et al., 2023). Out of nine threats, the top six, i.e., grassland burning during the breeding season, grassland succession into woodlands, thatch collection, habitat loss, and fragmentation, overgrazing by domestic cattle, and summer flooding, were selected for further relative threat ranking by the researcher in consultation and discussion with the FGD participants considering the WWF (2007) criteria.

2.3. Data analysis

The distribution pattern of the hispid hare was determined using the variance to mean ratio (S^2/a), where variance is calculated as $S^2 = \frac{1}{n}\sum(x-a)^2$, x is the number of pellet groups (signs) occurring per sampling unit., a is the mean of the x values, and n is the number of the sampling unit (Odum, 1971) as follows:

If $(S^2/a) = 1$, i.e., a random distribution,
If $(S^2/a) < 1$, i.e., a uniform distribution,
If $(S^2/a) > 1$, i.e., a clump distribution.

A multicollinearity test was run for all the chosen independent habitat predictors based on the variance inflation factor (VIF) using the "Faraway" package (Boomsma, 2014) in R x 64 4.0.3 (R Core Team, 2020). All habitat predictors were chosen for the final analysis,

Table 1
Detailed information on dependent and predictor variables used in the logistic regression model.

Variable	Variable type	Variable category	Values	Data source
Presence or absence of hispid hare	**Dependent**	Categorical	• Presence = 1 • Absence = 0	Field survey
Ground cover % (**GCo**)	**Predictors**	Categorical	• Low (0–25 %) = 1 • Moderate (26–50 %) = 2 • High (51–75 %) = 3 • Dense (76–100 %) = 4	Field survey
Habitat type (**HT**)		Categorical	• Tall grassland (grass > 2 m height) = 4 • Short grassland (grass 25 cm to 2 m in height) = 3 • Open grassland (grass < 25 cm in height) = 2 • Forest (Dominated by trees of any species) = 1	Field survey
Nearest distance to the water source (WD) (m)		Continuous	Range (4–500)	(USGS, 2021)
Ground condition (**GC**)		Categorical	• Wet (sticky consistency) = 1 • Dry (dusty consistency) = 2	Field survey
Dominant plant species (**DS**)		Categorical	• *Narenga porphyrocoma* = 1 • *Saccharum spontaneum = 2* • *Imperata cylindrical = 3* • *Themeda arundinacea = 4*	Field survey
Presence/absence of anthropogenic disturbance (plastics, jeep safari, controlled or uncontrolled burning, grass cutting) (**AD**)		Categorical	• Presence = 1 • Absence = 0	Field survey

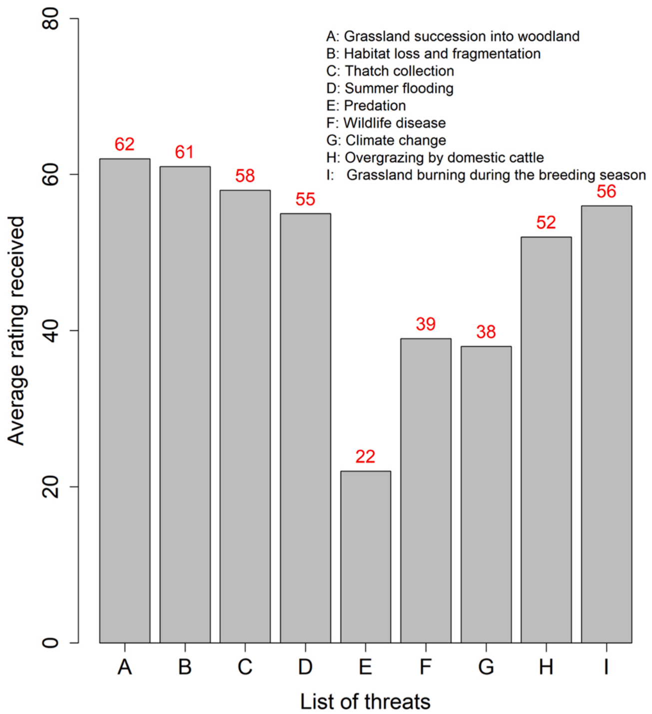

Fig. 3. Figure showing the average rating received by each threat. The top six threats were selected for the final threat ranking, as WWF (2007) described.

as none displayed multicollinearity, with tolerance values greater than 0.1 and VIF values lower than 10 (Bowerman and O'connell, 1990). Generalized linear models (GLMs) with binary distribution were used to calculate the likelihood of observing hispid hares associated with various habitat predictors (Table 1). Among six habitat predictors, only the nearest distance to a water source (WD) was used as a continuous variable, while the others were used as categorical variables. We used the global model 'dredge' function under the "MuMIn" package for our analysis (Barton, 2009). All potential models were built and were ranked using Akaike's information criterion with correction (AICc) for a small sample size (Barton and Barton, 2020). The leading candidate models were averaged to develop the final models (delta AIC ≤ 2) (Burnham and Anderson, 2001) using the "AICmodavg" package (Mazerolle and Mazerolle, 2017). The predictive performance of the best-fit model was calculated based on the area under curve (AUC) of the receiver operator characteristics (value range 1–0) by using the R package "ROCR" (Sing et al., 2005) (Fig. 4). Values between 0.7 and 0.8 were considered acceptable discrimination, 0.8–0.9 excellent discrimination, and > 0.9 superior discrimination (Hosmer et al., 2000).

The top six rated conservation threats were additionally ranked following a method of relative threat ranking (WWF, 2007) by considering four classification criteria, i.e., scope, severity, urgency, and irreversibility (Table 2) (NHWAP, 2015; Chhetri et al., 2020; Khulal et al., 2021). These six significant threats were assigned a relative rank ranging from 6 to 1, where 6 implies very high with severe effects and 1 indicates very low with minor consequences. Later, the total values of scope, severity, urgency, and irreversibility were used to rank the threats under four scales: very high (18.1– $\leq$ 24); high (12.1– $\leq$ 18); medium (6.1– $\leq$ 12); low ($\leq$ 6) (WWF,

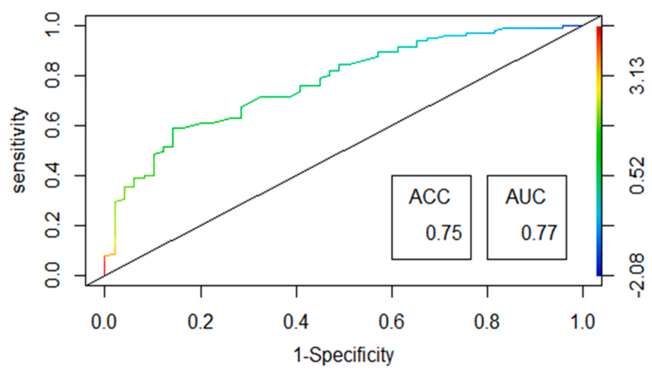

Fig. 4. Receiver operating curve for the best fit model with binary logistic regression. ACC = accuracy, AUC = area under curve.

2007; Koirala et al., 2020).

3. Results

3.1. Hispid hare distribution

Hispid hare presence was recorded in 9 sampling grids (0.5 km^2) among the systematically placed 12 sampling grids. Similarly, out of 154 circular plots laid out within the 12 sampling grids, 105 were used by hispid hares. The species was recorded from the areas of 24 Number Pillar, 3 Tale Machan, Singhpur Phanta, Shukla Post, 2 Tale Machan, Silalekh, Barkhaula post, Silgaudi Doban, Haraiya Phanta, Near Mahakali, Near Rani Tal, and Baba Tal. Most importantly, this study identifies and confirms a new distribution location of the species from the Baba Tal area (Fig. 1). Most hispid hare signs were recorded from Silalekh (37.14 %) followed by Barkhaula post (21.9 %) and 3 Tale Machan (16.3 %). The overall distribution of the hispid hare was clumped with a variance to mean ratio greater than 1 (**2.522**).

3.2. Hispid hare habitat use probability in relation to habitat predictors

Among the various sets of models generated from the binomial distribution, the model with an additive effect (Detection ~ Presence/absence of anthropogenic disturbance + Dominant plant species + Ground cover + Habitat type + Ground condition) had the lowest AICc (**179.65**) and the highest AIC weight (0.38), establishing it as the best model among the candidate model sets to explain the probability of hispid hare habitat use (Table 3). Moreover, resemblance model weight leads to model uncertainty among the identified habitat predictors. The dominant model's area under receiver operating curves (ROC) (GLM with binary logistic regression) was estimated to be 0.77 with an accuracy value of 0.75 (75 %), indicating an acceptable discriminatory ability (Fig. 4).

Further, five out of the pre-determined six habitat predictors, i.e., dense ground cover ($\beta = 1.300$, S.E = 0.555, P = 0.019), dry ground condition ($\beta = 1.138$, S.E = 0.419, P = 0.007), tall grassland habitat type ($\beta = 1.807$, S.E = 0.700, P = 0.010), *Saccharum spontaneum* as dominant plant species ($\beta = 1.048$, S.E = 0.532, P = 0.049), and presence of anthropogenic disturbance ($\beta = -1.128$, S.E = 0.413, P = 0.006), significantly affected the probability of detecting hispid hare in the study area (Table 4). Results of the model showed that the likelihood of detecting hispid hares increases with dense ground cover, dry ground conditions, tall grassland habitat types, and *Saccharum spontaneum* as the dominant plant species. In contrast, the probability of detecting hispid hare decreases with an increase in the presence of anthropogenic disturbances. However, we found no significant difference in the probability of observing hispid hare for the nearest distance to a water source (Table 4).

3.3. Major conservation threats to hispid hares

Our study ranked grassland burning during the breeding season and grassland succession into woodland as the most severe threats faced by the species. Similarly, habitat loss, fragmentation, and thatch collection were classified as high and medium threats, respectively. In contrast, the overgrazing of domestic cattle and summer floods were recognized as low-level threats (Table 5).

4. Discussion

Results from this study illuminate a crucial aspect of hispid hare conservation by revealing information of its distribution, habitat factors associated with its habitat use, and the major existing conservation threats.

4.1. Hispid hare distribution

Historically, the hispid hare was believed to reside in three protected areas of Nepal (ShNP, BNP, and CNP) (Oliver, 1980). Since the 1980s, the species has only been recorded from BNP and ShNP (Tandan et al., 2013). However, an individual hispid hare was rediscovered from Sukhibhar grassland in the CNP on 30 January 2016 by the team of Khadka et al. (2017) in a survey targeted at grassland birds, including the Bengal florican (*Houbaropsis bengalensis*). Previous studies in ShNP have recorded hispid hares from 24 Number Pillar, 3 Tale Machan, Singhpur Phanta, Shukla Post, 2 Tale Machan, Silalekh, Barkhaula post, Silgaudi Doban, Haraiya

Table 2
Interpretations of criteria used to rank each threat (adopted from WWF, 2007 and NHWAP, 2015).

Threat criterions	Definition
Scope	The percentages of a target (area for ecosystems, population for species) that will presumably become threatened within ten years if the present situation and patterns continue.
Severity	Within the scope, the damage extent caused by the threat to the target (area for ecosystems, population for species) can reasonably be expected in the next ten years if the present situation and patterns continue.
Urgency	The sense of emergency involved when taking measures to counter the threat and to avert the local extinction of the targeted population.
Irreversibility	The degree to which the effects of a threat can be undone and the target (area for ecosystems, population for species) affected by the threat restored if the threat is stopped.

Table 3
Factors influencing the detection of hispid hare are predicted by a generalized linear model with a binomial structure using second-order Akaike Information criterion scores (AICc, ΔAIC & AIC weight).

Component models *Binomial distribution*	df	LogLik	AICc	ΔAIC	Weights
Detection ~ (AD + GCo + HT + GC)	7	-82.44	179.65	0.00	0.38
Detection ~ (AD + HT + GC)	4	-86.12	180.51	0.86	0.25
Detection ~ (AD + DS + GCo + HT + GC)	8	-81.87	180.73	1.08	0.22
Detection ~ (AD + GCo + HT + GC + WD)	8	-82.27	181.52	1.87	0.15

[AD] Presence/absence of anthropogenic disturbance, [GCo] Ground cover %, [HT] Habitat type,
[GC] Ground condition, [DS] Dominant plant species, [WD] Nearest distance to the water source.

Table 4
Model-averaged coefficients of predictor variables associated with the probability of detecting hispid hare in Shuklaphanta National Park. The significant variables influencing hispid hare habitat use (Pr (> |z|) < 0.05) are denoted with * signs.

Predictors	*Estimate (β)*	*Standard Error (S.E)*	*Z-value*	*Pr (>|z|)*
Intercept	-1.067	0.735	-1.451	0.147
WD	0.001	0.002	0.519	0.604
Factor [GCo] 2	0.193	0.595	0.325	0.745
Factor [GCo] 3	0.185	0.586	0.316	0.752
Factor [GCo] 4	1.300	0.555	2.343	0.019*
Factor [GC] 2	1.138	0.419	2.715	0.007**
Factor [HT] 2	0.382	0.539	0.708	0.479
Factor [HT] 3	0.816	0.584	1.397	0.162
Factor [HT] 4	1.807	0.700	2.583	0.010**
Factor [DS] 2	1.048	0.532	1.970	0.049*
Factor [DS] 3	0.614	0.557	1.102	0.271
Factor [DS] 4	0.787	0.606	1.298	0.194
Factor [AD] 1	-1.128	0.413	-2.730	0.006**

Significance codes: 0 '***' 0.001 '**' 0.01 '*'.
[WD] Nearest distance to the water source, [GCo] Ground cover %, [GC] Ground condition, [HT] Habitat type, [DS] Dominant plant species, [AD] Presence/absence of anthropogenic disturbance.

Table 5
Relative ranking of the most severe threats recorded from the direct field survey and the focal group discussions. The total values of scope, severity, urgency, and irreversibility were used to rank the threats under four scales: very high (18.1– ≤ 24); high (12.1– ≤ 18); medium (6.1– ≤ 12); low (≤ 6).

Major threats	Scope	Severity	Urgency	Irreversibility	Total	Threat classification
Grassland burning during the breeding season	6	5	6	6	23	Very high
Grassland succession into woodlands	5	6	4	5	20	Very high
Thatch collection	3	3	3	3	12	Medium
Habitat loss and fragmentation	4	4	5	4	17	High
Overgrazing by domestic cattle	1	1	2	2	6	low
Summer flooding	2	2	1	1	6	low

Phanta, Near Mahakali, Near Rani Tal, Dhakna Ghat, and Piparia (Bell, 1986; Aryal et al., 2012; Chand et al., 2017; Sadadev et al., 2021). However, our study identified and confirmed a new distribution location near the Baba Tal area. The confirmed presence of the species from recent locations have alerted the park manager to strengthen conservation efforts for the long-term survival of the hispid hare. In addition, it has urged researchers and conservationists to perform immediate assessments of possible distribution ranges and habitats across the entire distribution range. Better food availability, consisting of the grass species *Imperata cylindrical and Saccharum spontaneum,* and low human pressure in the study area could be possible reasons for expanding the hispid hare habitat range. Also, changing habitat conditions due to the impacts of climate change may have pushed the species to new locations (Chhetri et al., 2020).

Pant et al. (2021) also revealed that the ShNP has a less suitable habitat than other protected areas of Nepal for the greater one-horned rhinoceros (*Rhinoceros unicornis*), a grassland-dependent species with similar feeding preferences as the hispid hare (Subedi et al., 2017). Thus, further studies focusing on the current and future suitable habitat refugia for hispid hares are essential, considering bioclimatic variables to ensure and implement a long-term habitat-centric conservation strategy. This will also benefit other threatened grassland-dependent fauna like the Bengal florican.

Aryal et al. (2012) reported a higher number of hispid hare signs from 3 Tale Machan, which coincides with our findings that the majority of signs were recorded from Silalekh followed by Barkhaula post and 3 Tale Machan. The overall distribution was clumped, indicating that the hispid hare uses the same sites during specific periods of the year (Maheswaran, 2002). Sadadev et al. (2021) also reported a clumped distribution for hispid hares in burned and unburned plots in ShNP, which supports our results.

4.2. Factors influencing the habitat use of hispid hares

We found that tall grassland significantly influenced the habitat use of hispid hares. Aryal et al. (2012) also reported that the species usually prefers tall grassland that exists before and after grassland burning practices. Burning practices are conducted annually in ShNP from November to April (Sadadev et al., 2021). Similarly, Chand et al. (2017) reported that hispid hares showed a higher preference for tall grassland in ShNP during the winter and summer seasons. Additional studies carried out by Nidup (2018) in Bhutan, and Rastogi et al. (2020), and Nath and Machary (2015) in India also reported a similar preference for hispid hares. This may be because tall grasslands are more likely to offer cover for adults by increasing their breeding success (Aryal et al., 2012) and by reducing the risk of predation caused by their progeny being more vulnerable to avian predators (vultures, raptors, and eagles) in places where short grasses predominate. In addition, the hispid hare feeds on the inner sap of grasses growing 15 cm aboveground (Maheshwaran and Kumar, 2008), which could explain the preference for tall grassland.

Our study determined that hispid hares preferred dense ground cover, which is parallel to the findings of Yadav (2006), Nath et al. (2010), and Aryal et al. (2012). Similarly, a study conducted by Chand et al. (2017) in ShNP reported that the pellet group deposition rate increased when ground covers increased from moderate to dense, which supports our study. Resting and feeding are two main reasons why hispid hares prefer thick ground cover, along with dense cover potentially being a better place for successful breeding (Maheswaran, 2002). Further, hispid hares preferred dry ground conditions over wet ground conditions in our study. This finding is parallel to the results of a study conducted in ShNP by Yadav et al. (2008) and in Manas National Park of India by Nath and Machary (2015). In Nepal, two out of three females captured in the months of January and February were found to be pregnant (Oliver, 1984, 1985; Bell, 1986, 1987; Nowak, 1999). Utilizing dry ground conditions can therefore be linked to nesting and rearing young during the breeding season, as wet ground conditions may lead to juvenile mortality due to cold seasonal conditions. However, Maheswaran (2002) postulated that the hispid hare breeding season might vary from place to place. This postulate requires scientific validation by examining the breeding season of hispid hares at various geographic locations.

We found that hispid hare detectability increased with an increase in habitats dominated by the grass species *Saccharum spontaneum*, which concurs with an investigation by Yadav (2006). Their study reported *Narenga porphyrocoma* as the primary food species consumed by hispid hares followed by *Imperata cylindrica, Saccharum spontaneum,* and the leaves of *Cymbopogon spp.* Similarly, a diet analysis by Aryal et al. (2012) in ShNP revealed that *Saccharum spontaneum* and *Imperata cylindrica* occurred commonly in the hispid hare diet, which supports our findings.

We identified that hispid hare detection decreased with an increase in anthropogenic disturbances. Bhatta (1999) reported that local people used grasslands for farming and other purposes like grass for cattle, roofing, and fuel, which consequently leads to a reduction in favorable habitat for grassland-dependent wildlife, including the hispid hare (Aryal and Yadav, 2010). Cosgriff (1997) reported that greater one-horned rhinoceros disturbed by tourism activities avoided their typical habitats and escaped to isolated locations in CNP. All these pieces of evidence support the findings of our study. Similar research is essential in understanding the impact of ecotourism activity on the ecology and behavior of hispid hares in Nepal.

4.3. Major conservation threats to hispid hares

We determined grassland burning during the breeding season as the most severe threat to hispid hares because the species prefers dense coverage. The ShNP authorities, with support from local people, annually burn the grasslands to promote grass regrowth and a better grazing environment for wild animals (Aryal et al., 2012). As the primary breeding season of hispid hares coincides with this period (Bell, 1986, 1987), grassland burning most likely harms hispid hare breeding success (Sadadev et al., 2021). Nevertheless, alternate-year burning practices may have a more significant positive impact on the distribution and survival of this endangered species (Sadadev et al., 2021). Thus, we suggest that grassland burning must be performed selectively, patch by patch, to allow resident hares to escape from the intense grassland burning effect. Further, conservation managers must ensure that this selective grassland burning strategy does not overlap with the breeding season of the Bengal florican, another threatened species that shares similar habitat attributes as the hispid hare (Khadka et al., 2017; Prasai et al., 2021). This should enhance the breeding success and ensure the long-term conservation of the Bengal florican.

Our study further identified grassland succession into woodland as another severe threat. Maheshwaran and Kumar (2008) also reported that the conversion of grasslands into woodlands had become a severe threat to the existence of hispid hares in Jaldapara Wildlife Sanctuary in India because it reduces the important grass vegetation, which severely affects the food and cover requirements of this grassland-obligatory species. Similarly, Nidup (2018) reported the succession of grassland into woodland by *Bombax ceiba*, *Dillenia pentagyna,* and *Lagerstroemia parviflora* as a significant threat in Royal Manas National Park in Bhutan. Aryal and Yadav (2019) added that suitable habitat for grassland specialist species, including the hispid hare, is reduced by the natural succession of grassland into woods.

We ranked habitat loss and fragmentation as a high-level threat, as evidenced by other studies (Nath and Machary, 2015) in Manas National Park of Assam India. Between 1994 and 2005, the suitable habitat of the hispid hare declined (quantitatively and qualitatively) by 20–50 %, and this decline rate continued until 2014 (Molur et al., 2005). Also, according to recent literature, hispid hare habitat destruction has continued due to encroachment, expansion of agricultural land, logging, and other construction activities (Yadav et al., 2008; Aryal et al., 2012; Tandan et al., 2013; Nath and Machary, 2015; Nidup, 2018). This is a significant challenge for the species' long-term survival in its natural habitat.

Thatch collection is additionally identified as a moderate threat to the hispid hare. Several other studies, such as Maheswaran (2002), Nath and Machary (2015), and Chand et al. (2017), have shown unsustainable thatch harvesting to be a threat to the hispid hare. This unsustainable harvesting for roofing (Bhatta, 1999) has destroyed the primary habitat of grassland-dependent species, including the hispid hare (Aryal et al., 2012). Finally, summer flooding and overgrazing by domestic cattle are ranked as the least important threats to the species. In contrast to our results, Aryal et al. (2012) discussed that floodwater from the Mahakali River submerges the grassland, which may lead to offspring mortality and may halt population growth and elevate the risk of species extinctions Similarly, Bhatta (1999), Chand et al. (2017), and Regmi et al. (2022) reported overgrazing by domestic cattle as an existing threat to grassland-dependent species in ShNP, while Bhatta (1999), Chand et al. (2017), and Regmi et al. (2022) reported overgrazing by domestic cattle as an existing threat to grassland-dependent species in ShNP. Our findings will inform the park managers and local government and help them formulate and plan suitable conservation measures that will contribute to maintaining a viable population of this elusive and endangered species. Additionally, conservation awareness and education programs with the active involvement of local grassland-dependent communities that provide these communities with alternatives for the grass resources are essential for substantially reducing anthropogenic pressure within hispid hare habitats.

5. Conclusions and conservation implications

This study identified the current distribution pattern of hispid hares, factors affecting the detectability of the species with respect to various habitat predictors, and the existing major conservation threats in ShNP in Nepal. We found that the overall distribution of the hispid hare was clumped, and a new distribution location was confirmed around the Baba Tal area. The chance of observing hispid hare increased with increases in ground cover, dry ground condition, tall grassland habitat type, and *Saccharum spontaneum* as a dominant plant species, while it decreased with an increase in the presence of anthropogenic disturbances. Likewise, grassland burning during the breeding season and grassland succession into woodland were identified as the most severe threats. Concurrently, habitat loss, fragmentation, and thatch collection ranked high and medium threats, respectively. By recognizing that adopted grassland burning practices during the breeding season are a severe threat, we recommend changing the timing and practice of annual grassland burning. Conservation managers should adopt selective grassland burning practices, patch by patch, and avoid the breeding season of hispid hares and Bengal florican. We also recommend adopting a scientific grassland management strategy to halt grassland succession into woodlands that will help protect and enhance the habitat conditions of the hispid hare. Further, our findings will be helpful for park managers and the local government in formulating and planning effective conservation measures, which will ultimately help to maintain a viable population of this elusive and endangered species.

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.

Data Availability

Data will be made available on request.

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