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Authors
Acharya, Paras Mani
Thainiramit, Panu
Techato, Kuaanan
et al.

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Predicting the distribution and habitat suitability of the smooth-coated otter (*Lutrogale perspicillata*) in lowland Nepal

Paras Mani Acharya [a], Panu Thainiramit [a], Kuaanan Techato [a], Suraj Baral [b], Naresh Rimal [c], Melissa Savage [d], Ahimsa Campos-Arceiz [e], Dinesh Neupane [b,e,*]

[a] *Faculty of Environmental Management, Prince of Songkla University, Thailand*
[b] *Resources Himalaya Foundation, Sanepa, Lalitpur, Nepal*
[c] *Armed Police Force Command and Staff College, Kathmandu, Nepal*
[d] *University of California, Los Angeles, USA*
[e] *Southeast Asia Biodiversity Research Institute, Chinese Academy of Sciences, and Center for Integrative Conservation, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla, Yunnan 666303, China*

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ABSTRACT

Ever increasing anthropogenic pressures and natural threats to freshwater ecosystems are impacting global biodiversity. Otters are an indicator species that have an important role in maintaining the integrity and stability of wetland ecosystems. A lack of information on essential variables of otter ecology in the Himalaya range, including suitable potential habitat and site occupancy, hampers otter conservation. In this study, we analyze the geographic range, habitat suitability, and landscape connectivity for the smooth-coated otter (*Lutrogale perspicillata*) in lowland areas of Nepal. Using 655 presence points collected between 2010 and 2018, we created habitat suitability models using an ensemble of small models (ESMs) derived from MaxEnt techniques to understand the variables influencing smooth-coated otter distribution in the country. The model predicted the distribution of smooth-coated otters with high accuracy (AUC = 0.89 ± 0.03, Boyce's Index = 0.95 ± 0.02). The model identified distance to water, precipitation in the driest month, Normalized Difference Vegetation Index, precipitation in the warmest quarter, and precipitation in the driest quarter, as the top five weighted variables that highly influenced the habitat suitability of smooth-coated otters, and identified 12 core areas with 14 potential connectivity linkages in only 2374 km^2 of highly suitable habitat in Nepal. Importantly, suitable habitat was found to be highly concentrated in protected areas, particularly in Bardia and Shuklaphanta National Parks, having the only significant permeability of linkages between these core areas. All seven provinces had very small amounts of highly suitable habitat, likely due to the low abundance of natural freshwater lakes and aquaculture ponds, with the exception of Sudurpaschim Province, with only 19.82%, and Lumbini Province, with 5.18%, of highly suitable habitat. While accounting for little land area, the aquaculture ponds may provide important prey sources for otters, and consequently may create conflict with local farmers in the future. Appropriate management intervention, including habitat restoration, the integration of otter conservation strategies into wetland policies, specifically in the Ramsar site management plans, are urgently needed for the survival of the species in Nepal.

* Corresponding author at: Resources Himalaya Foundation, Sanepa, Lalitpur, Nepal.
E-mail address: dineshkneupane@gmail.com (D. Neupane).

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1. Introduction

Freshwater ecosystems have high conservation significance for the crucial ecosystem functions and services they contribute, including providing key habitat for flagship aquatic species such as dolphins, gharials, and otters (Hammerschlag et al., 2019; Desforges et al., 2022; Acharya et al., 2022). Freshwater ecosystems occupy < 1% of the earth's surface, yet they support 12% of all known species, including 30% of all vertebrates (Strayer and Dudgeon, 2010; Garcia-Moreno et al., 2014; Darwall et al., 2018). Freshwater ecosystems are degrading three times faster than terrestrial ecosystems, due to ever-increasing anthropogenic pressures, including climate change (Dudgeon et al., 2006; Strayer and Dudgeon, 2010; Gardner and Finlayson, 2018). Freshwater vertebrates are experiencing the largest decline (84% decline in number of populations since 1970), four times faster than in terrestrial or marine ecosystems (Reid et al., 2019). Consequently, around 13% of inland wetland-dependent mammals are globally threatened, and 3% of them are critically endangered (Collen et al., 2014). Protected areas and other area-based conservation strategies have primarily targeted terrestrial and marine biodiversity, focusing less on the conservation of freshwater ecosystems (Abell et al., 2017).

Otters (Subfamily Lutrinae) are semi-aquatic predators and highly threatened due to heavy anthropogenic pressure such as hunting, disturbance, pollution, and overfishing (Kruuk, 2006). As top predators, otters serve as a keystone and biological indicator species for assessing ecological integrity, and are highly vulnerable to habitat alteration and environmental pollution (Kruuk, 2006; Acharya, 2017). There are thirteen species of otters that live on all continents except Antarctica and Australasia. Five species of otters live in Asia: the sea otter (*Enhydra lutris*), hairy-nosed otter (*Lutra sumatrana*), Asian small-clawed otter (*Aonyx cinereus*), Eurasian otter (*Lutra lutra*), and smooth-coated otter (*Lutrogale perspicillata*). The latter three species have been documented in Nepal (Acharya and Rajbhandari, 2011), although knowledge of the status of their populations is uneven and limited (Acharya and Lamsal, 2010; Acharya and Rajbhandari, 2011, Basnet et al., 2020). A continuous decline has been documented for smooth-coated otters (Acharya and Lamsal, 2010; Acharya and Rajbhandari, 2011) and Eurasian otters (Shrestha et al., 2021), while small-clawed otters have not been documented in Nepal since 1839 (Hodgson, 1839). The distribution range of these two species in Nepal overlap very little, as the smooth-coated otter is found in the lowland Terai while the Eurasian otter is found in mountain rivers, leading to a low probability of interaction. However, there is an evidence of such interaction between these two species in Thailand, where both species experience a resource overlap (Kruuk et al., 1994).

The smooth-coated otter has a wide distribution range, from Indonesia through southwestern China, Bhutan, Nepal, India, and Pakistan (Hussain et al. 2008; Moretti et al., 2017; Raman et al., 2019). They inhabit large rivers, lakes, estuaries, coastal mangrove swamps, and prefer undisturbed riparian forests or scrub (Kruuk, 2006; Abdul-Patah et al., 2014). Historically, Nepal's lowland (Terai) and Himalayas had some evidence of distribution of the smooth-coated otter (Hodgson, 1839; named as *Lutra tarayensis*). Evidence of their presence has been documented in the braided channels of major rivers with slow current and shallow depth (Acharya and Lamsal, 2010; Acharya, 2017, 2016). However, smooth-coated otters have experienced population declines and habitat restriction through disturbances in river channels due to stone and gravel extraction, fishing and hunting (Acharya, 2017). Importantly, the illegal trade in otters, and ever-increasing human disturbances, including infrastructure development, construction of dams, irrigation intakes, sedimentation, urban expansion, and agricultural and industrial pollution have reduced otter populations and their natural habitats in Nepal (Acharya, 2017; Acharya and Rajbhandari, 2011; Savage and Shrestha, 2018). The smooth-coated otter is listed as vulnerable in the IUCN Red List (Khoo and Sivasothi, 2018) and on Appendix I of the Convention on International Trade in Endangered Species.

Knowledge of species distribution and habitat requirements is crucial to the conservation and management of this threatened riverine indicator species. Although Jamwal et al. (2022) first documented smooth-coated otter distribution modelling in the trans-Himalaya region, country-wise modeling of the species has not been studied yet done in Nepal. This study evaluates the distribution range, habitat suitability, and landscape connectivity for smooth-coated otters through modeling of its occurrence in lowland Nepal. Study outcomes include species distribution mapping and identification of the potential range of smooth-coated otters in Nepal.

With the growing availability of georeferenced species presence points and environmental data, species distribution models (SDMs) are now widely used to investigate species distributions (Peterson et al., 2011; Zhao et al., 2020), the environmental pressures affecting them, habitat suitability, and functional connectivity (Cianfrani et al., 2013; Neupane et al., 2022) and to offer solutions for conservation and wildlife management (Sousa-Silva et al., 2014; Gomes et al., 2018; Neupane et al., 2022; Baral et al., 2023). SDMs relate environmental variables to the likelihood of occurrence of the species (Hirzel et al., 2006; Pearson, 2007; Hirzel and Le Lay, 2008). Two basic approaches have been applied in conducting SDMs: presence-only and presence-absence. For many elusive animals, such as otters, finding true absence data is unfeasible, thus a presence-only approach is widely used. SDMs link environmental and geographic space with the locations of animals and project potential locations for species distributions (Peterson, 2003; Guisan and Thuiller, 2005; Hirzel and Le Lay, 2008). However, SDMs cannot predict accurately with limited presence points or overfit the model with sample biases (Radomski et al., 2022), whereas MaxEnt can create a distribution model using a small presence point set (Phillips et al., 2006; Phillips and Dudík, 2008) with the highest performance and greater accuracy (Elith et al., 2006; Elith et al., 2011). Thus, here we used an ensemble of small models (ESMs) through MaxEnt to model smooth-coated otter distribution and habitat suitability in Nepal.

ESMs are an appropriate approach, as they minimize the model overfitting even with a small set of presence points (Lomba et al., 2010; Breiner et al., 2015; Breiner et al., 2018). Here, however, we used 124 presence points, after filtering. An ESM strategy involves building many models by fitting bivariate models of presence/(pseudo) absence with two predictor variables at a time, creating an ensemble of "small" models weighted by each bivariate model performance.

2. Materials and methods

2.1. Study area

Nepal is highly diverse ecologically, with habitats ranging from lowland forests at < 100 masl to ice-covered peaks at over 8000 masl. About 83% of Nepal's landmass lies in the mountains and 17% is lowland in the southern plains (< 500 m). Climate varies from tropical lowlands in the south to alpine cold semi-desert in the Himalayan zone. This study focused on the habitat suitability analysis of the smooth-coated otter in the lowland Nepal, particularly below 1000 masl as smooth-coated otters primarily inhabit the plains, occurring mostly in areas of low elevation up to 700 masl.

Our study addresses smooth-coated otter occurrence in the lowland regions, or Terai (area: 20170 km^2), a northern extension of the Indo-Gangetic Plain (LRMP, 1986; DFRS, 2014). This region includes five national parks (Parsa, Chitwan, Banke, Bardia, and Suklaphanta NPs), one wildlife reserve (Koshi Tappu W*R*), and a conservation area (Blackbuck CA). The region also contains four wetlands of international importance (Ramsar sites): Koshi Tappu W*R*, Beeshazari Lake Complex, Jagdishpur Reservoir, and Ghodaghodi Lake complex). The protected areas of lowland Nepal comprise a wide range of freshwater wetland habitats that offer potential habitat for smooth-coated otters. Major rivers originating from the Himalayan glaciers such as the Koshi, Narayani, Gandaki, and Mahakali glaciers drain through the Terai region providing suitable habitat for otters. A high in-migration of people from the hill region to the Terai region of Nepal has created heavy and accelerating pressure on forest and wetland resources. Recent human population growth in the Terai region has been recorded at a rate of 1.75% per year for a population density of 392 persons/km^2 (CBS, 2012). The country is administratively divided into seven provinces, Koshi, Madhesh, Bagmati, Gandaki, Lumbini, Karnali, and Sudurpaschim (Fig. 1). Neighboring provinces have often share river systems. For example, the Koshi River system flows in both Koshi and Madhesh Provinces; Madhesh and Bagmati Provinces are separated by the Bagmati River system; the Gandaki River system flows through both Bagmati and Gandaki Provinces; and the Karnali River system flows through Karnali and Sudurpaschim Provinces.

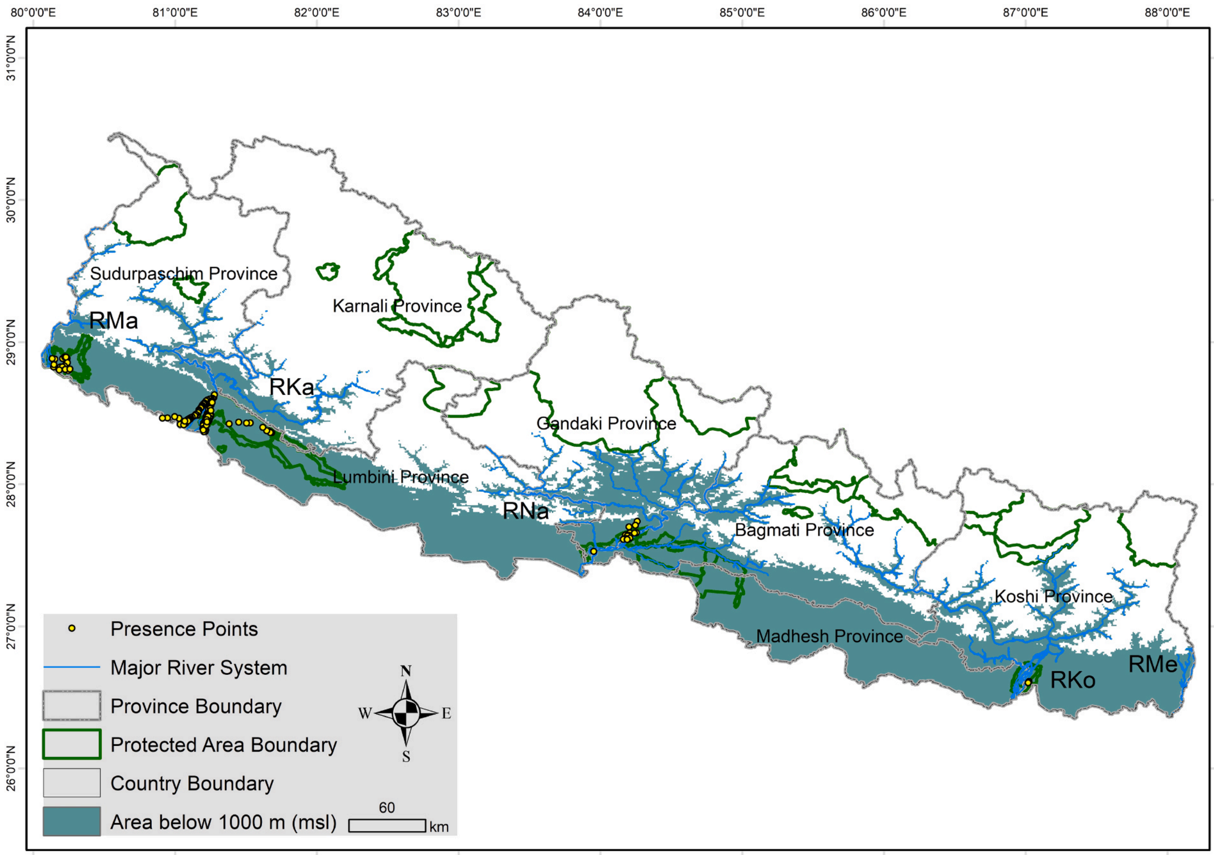

Fig. 1. Map of Nepal showing the boundaries of protected areas, major river systems, boundaries of provinces, areas below 1000 masl, and sampled presence points of smooth-coated otter used for ensemble of small models. Major river systems were denoted by Rma: Mahakali River system, Rka: Karnali River system, RNa: Narayani River system, RKo: Koshi River system, and Rme: Mechi River system.

2.2. Presence points and environmental variables

We gathered a total of 655 occurrence points for smooth-coated otters in the Terai region using published literature, reports, and field surveys carried out in between 2010 and 2018. Surveys of smooth-coated otters were carried out by the leading author (P. M. Acharya) in Chitwan National Park (2010–2012) (Acharya and Rajbhandari, 2012), in the Babai Valley of Bardia National Park (2012) (Acharya and Rajbhandari, 2013), and the Lower Karnali River basin in Bardia National Park (2016–2017) (Acharya, 2017). We also used presence points reported from Shuklaphanta National Park from Bohara (2018) and in Koshi Tappu Wildlife Reserve from Mishra et al. (2022). The surveys were carried out in a standard protocol by searching for signs (track and scat) as a proxy for the presence points of otter along the river on both sides of the banks through walking and/or boat. Most of the presence points were aggregated in or near protected areas, and there were intensive efforts in river channels outside of protected areas, yet no evidence of such presence was gathered. We then conducted a spatial filtering of all occurrence data resulting in 124 occurrence data points to reduce overfitting to sampling bias.

A set of environmental variables ($n = 29$) consisting of climatic, topographic, habitat, and disturbance data, as described in the literature, and soil-related information (Table S1) were used to model the potential distribution of smooth-coated otters. Soil-related information was considered an important variable as the species prefers sandy substratum for grooming (Anoop and Hussain, 2004; Melquist et al., 2003). We obtained 19 bioclimatic variables based on a 30-year climatological record from 1970 to 2000 (climatic predictors) from CHELSA Climatologies ver. 2.1 with a resolution of 30 arc-seconds and all rasterized at a resolution of about 1 km (Fick and Hijmans, 2017; Karger et al., 2017). We acquired elevation data from a 30-sec Shuttle Radar Topography Mission (SRTM) derived from WorldClim 2.1 (Fick and Hijmans, 2017). We derived bank slope from the downloaded elevation data and used it as another topographic variable for modeling. We downloaded the land use land cover at 500 m resolution (LULC) data from Moderate Resolution Imaging Spectroradiometer (MODIS) Land cover type (MCD12Q1) Version 6 (Friedl and Sulla-Menashe, 2019; Gray et al., 2019) for the year 2019 from Google Earth Engine (GEE), extracted grassland and built-up area from the data, and created a raster layer of the proportion of the grassland and built-up area across the study area in a moving window of 17 km length radius. Such radius length was coherent with the average home range of the smooth-coated otter (Hussain, 1993). The same raster dataset was used to derive Euclidean distance from the respective land cover data. Additionally, we downloaded a wetland dataset comprising open water, swamps, marshes, and floodplains (Gumbricht et al., 2017) for Nepal to calculate the Euclidean distance from the nearest pixel where wetlands were present. Annual mean Normalized Difference Vegetation Index (NDVI) and mean Normalized Difference Wetness Index (NDWI) data from MODIS were downloaded from GEE. NDVI is a measure of vegetation productivity and an indicator of forest degradation (Meneses-Tovar, 2011). We downloaded MODIS NDVI (Normalized Difference Vegetation Index) to calculate the average NDVI in Nepal from 2000 to 2020 from Google Earth Engine. Euclidean distance and proportion of grassland, wetlands, NDVI, and NDWI were used as the habitat-related variables. The proportion of sand in the soil at 0–10 cm depth (Hengl, 2018a; b) was included as the soil-related variables for the model. Finally, the global human footprint (WCS and CHESIN, 2005) data were used as a disturbance-related variable. The Variance Inflation Factor (VIF) test was used to determine multicollinearity and also eliminated highly correlated variables ($VIF \geq 5$; Cobos et al., 2019). With this, we retained 14 uncorrelated covariates after checking for multicollinearity between variables for the final distribution model (Table 1).

2.3. Habitat suitability model building and validation

MaxEnt is a popular tool to predict species distributions and is able to cope well with sparse, irregularly sampled data and minor location errors (Elith et al., 2006). MaxEnt is an area of machine learning and can be considered an effective and reliable method to make inferences from incomplete datasets and has been used to predict species distributions using presence-only information (Phillips et al., 2006; Phillips and Dudík, 2008). It is appropriate for modeling distributions/environmental niches from presence-only species locations (Phillips et al., 2006; Elith et al., 2011; Merow et al., 2013). MaxEnt estimates the distribution of a species by finding the

Table 1
Final environmental variables used for modeling the distribution of smooth-coated otter with their VIF values.

Variable	VIF value
Mean Temperature of Wettest Quarter	3.02
Precipitation in Driest Month	4.42
Precipitation in Driest Quarter	2.11
Precipitation in Warmest Quarter	2.46
Distance to grassland	1.19
Distance to roads	1.35
Distance to settlement	3.07
Distance to water	2.93
Human footprint	1.90
NDVI	2.03
Grassland proportion	1.63
Settlement proportion	1.78
Sand	1.24
Slope	2.53

distribution with maximum entropy (i.e., close to geographically uniform) subject to constraints derived from environmental conditions at recorded occurrence locations (Phillips et al., 2017). The model uses a sample of background locations to contrast against presence locations (Merow et al., 2013; Gomes et al., 2018). It has the advantage of not requiring absence data for predicting species distribution (Elith et al., 2011; Phillips et al., 2006, 2017). MaxEnt outperforms many comparative studies (Elith et al., 2006; Peterson et al., 2007; Guisan et al., 2007; Wisz et al., 2008; Gomes et al., 2018).

We created smooth-coated otter habitat suitability models using an Ensemble of Small Models (ESM), a technique that models a species' distribution using straightforward binary models before combining all potential models into a single model. ESM is a good choice for distribution modeling since it minimizes the model overfitting (Radomski et al., 2022), which is acceptable given the small sample size of presence points available in this investigation. We chose this method because it can describe complex environmental relationships and has higher accuracy with a small sample size based on jackknife testing (Pearson et al., 2007). Additionally, based on various validation measures like the Area Under Curve of the Receiver's Operating Curve (AUC), Boyce Index, True Skill Statistics (TSS), and Kappa values, we chose ESM with a single algorithm because it predicts the distribution of a species similarly to an ESM of multiple algorithms (Breiner et al., 2018).

To calibrate the model, we utilized the Ecospat R Package, version 3.2. To calibrate each bivariate model, 70% of the presence data and 2500 randomly chosen background points within a 20 km radius of each observed locality were used. The buffer distance is a technique used to lessen any spatial bias that may have been added to the presence points as a result of non-random sampling. As the background points are constrained to a smaller portion of the study's scope, the buffer enables a superior prediction (Phillips and Dudík, 2008). After that, we used the Boyce Index to analyze each bivariate model, and eliminated any models with an index value below 0.5.

We then developed a final ensemble prediction by averaging the chosen models and weighting them according to the Boyce Index (Radomski et al., 2022). Three model assessment measures usually used in presence-only models such as AUC (Fielding and Bell, 1997), TSS (Allouche et al., 2006), and the Boyce Index (Hirzel et al., 2006) were employed to assess the model's performance (Guisan et al., 2007). We utilized the ratio of the additional weight (Boyce Index) of a specific variable to the sum of the weights of all the variables employed in the ensemble to assess the relative importance of a variable on the ensemble model. To determine the variable response, we plotted the value of a specific variable along with its suitability for the training area (20 km from the closest known presence points) using the R Package "ggplot2" Ver. 3.3.3 (Wickham, 2016). To classify habitat suitability, we used thresholds following as low (0.0–0.2), medium (0.2–0.4), high (0.4–0.6), and optimal (> 0.6). Later, we merged high and optimal suitability into higher suitability to discuss in paper.

2.4. Landscape connectivity analysis

We used identified core habitat and the obtained resistance raster to model the connectivity of the smooth-coated otter habitat in the study area. We used Core Mapper in the Gnarly Landscape Utility Tool (Shirk and McRae, 2013) for ArcGIS Pro (Esri, 2022) to calculate the core habitat for the smooth-coated otters. Additionally, the obtained habitat suitability model was inverted and scaled between 1 and 100 to simulate the difficulty of the movement in each pixel. Finally, we used the Linkage Mapper Tool (McRae and Kavanagh, 2011) in ArcGIS Pro to build the least-cost paths between the identified cores. We used the ratio of Least Cost Path (LCP) distance and Cost Weighted Distance (CWD) to calculate the importance of the identified corridors (Dutta et al., 2016) for the smooth-coated otters.

Table 2
Relative variable importance of the predictor variables as predicted by the ensemble of small models (ESM) for smooth-coated otter presence in Nepal.

Variable	Relative Variable Importance (%)
Climatic	
BIO18 (Precipitation in warmest quarter)	15.16
BIO17 (Precipitation in driest quarter)	15.10
BIO14 (Precipitation in driest month)	15.91
BIO8 (Mean temperature of the wettest quarter)	14.38
Topographical	
Bank slope	15.07
Habitat-related	
NDVI	15.87
Sand	14.10
Distance to water	20.24
Grassland proportion	14.95
Distance to grassland	14.03
Anthropogenic	
Settlement proportion	14.74
Distance to road	12.64
Distance to settlement	12.64
Human footprint	11.50

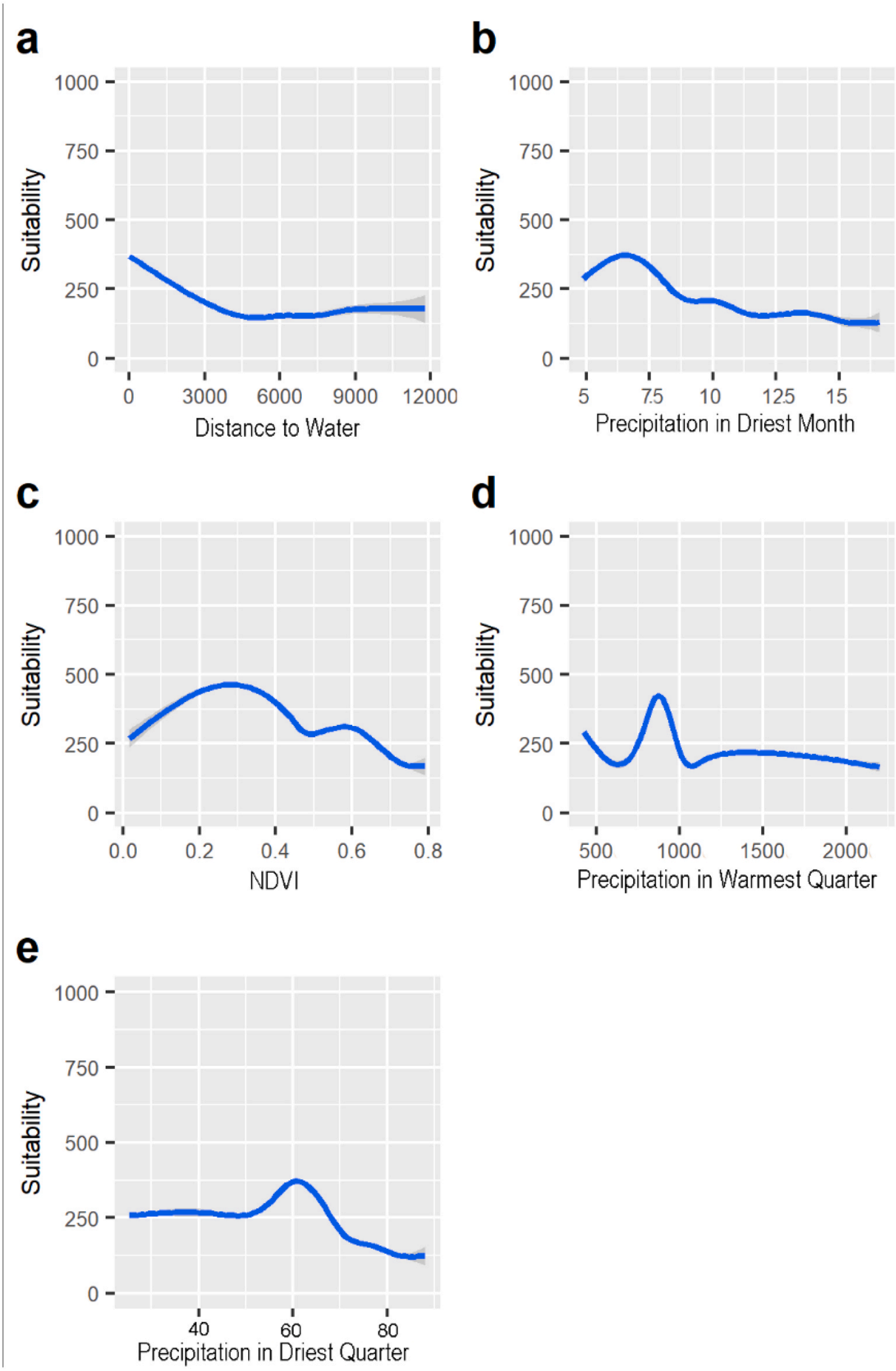

Fig. 2. Response curves for the top five weighted variables to model smooth-coated otter distribution in Nepal using the ESM approach. The response curves were derived from the model using both bioclimatic and environmental variables.

3. Results

3.1. Model performance and variable importance

The ESM model predicted the distribution of smooth-coated otters with high accuracy (AUC= 0.89 ± 0.03, Boyce's Index = 0.95 ± 0.02). Table 2 shows the contributions of the variables in modeling the habitat suitability of the species. The top five weighted variables that were strong predictors in determining distribution and habitat suitability included the distance to water (relative importance = 20.24%), precipitation in the driest month (15.91%), NDVI (15.87%), precipitation in the warmest quarter (15.16%), and precipitation in the driest quarter (15.10%) (Table 2). The cumulative contribution of these five predictors is 82.28%.

The response curve analysis (Fig. 2) suggests that smooth-coated otters prefer areas very near to waterbodies (within 3 km), precipitation between 5 and 7.5 mm in the driest month, intermediate values of NDVI (0.2–0.4), precipitation between 800 and 900 mm in the warmest quarter, and precipitation of an average of 60 mm in the driest quarter.

3.2. Habitat suitability

The habitat suitability map indicates that around 90 km^2 of the area investigated constitutes optimal suitability for the species while 2284 km^2 constitutes high suitability. Of these suitable areas, most are in western and far-western Nepal, particularly within Bardia NP and Shuklaphanta NP (Fig. 3). Moderate suitable habitat also occurs along major rivers in the Terai region, however a greater percentage of it lies in these two parks.

Since major river systems flow within the definite provincial boundaries, we assessed the habitat suitability at provincial level. A small percentage of optimal habitat for smooth-coated otters was found in the Sudurpaschim (0.52%) and Lumbini (0.48%) Provinces while Koshi, Madhesh, Bagmati, Gandaki and Karnali Provinces lacked any optimal suitability habitat. A relatively small amount of highly suitable habitat was found in all seven provinces, including 19.82% in Sudurpaschim Province and 5.18% in Lumbini Province (Table 3).

Bardia NP and Shuklaphanta NP in western Nepal provided only a small portion, 3.31% and 3.01% respectively, of optimal suitability habitat. Suklaphanta NP in western Nepal and Koshi Tappu W*R* in eastern Nepal offer high suitability habitat of 82.15% and 40.31% respectively. In terms of habitat suitability in the buffer areas of the Terai protected areas, only Bardia NP in western Nepal had

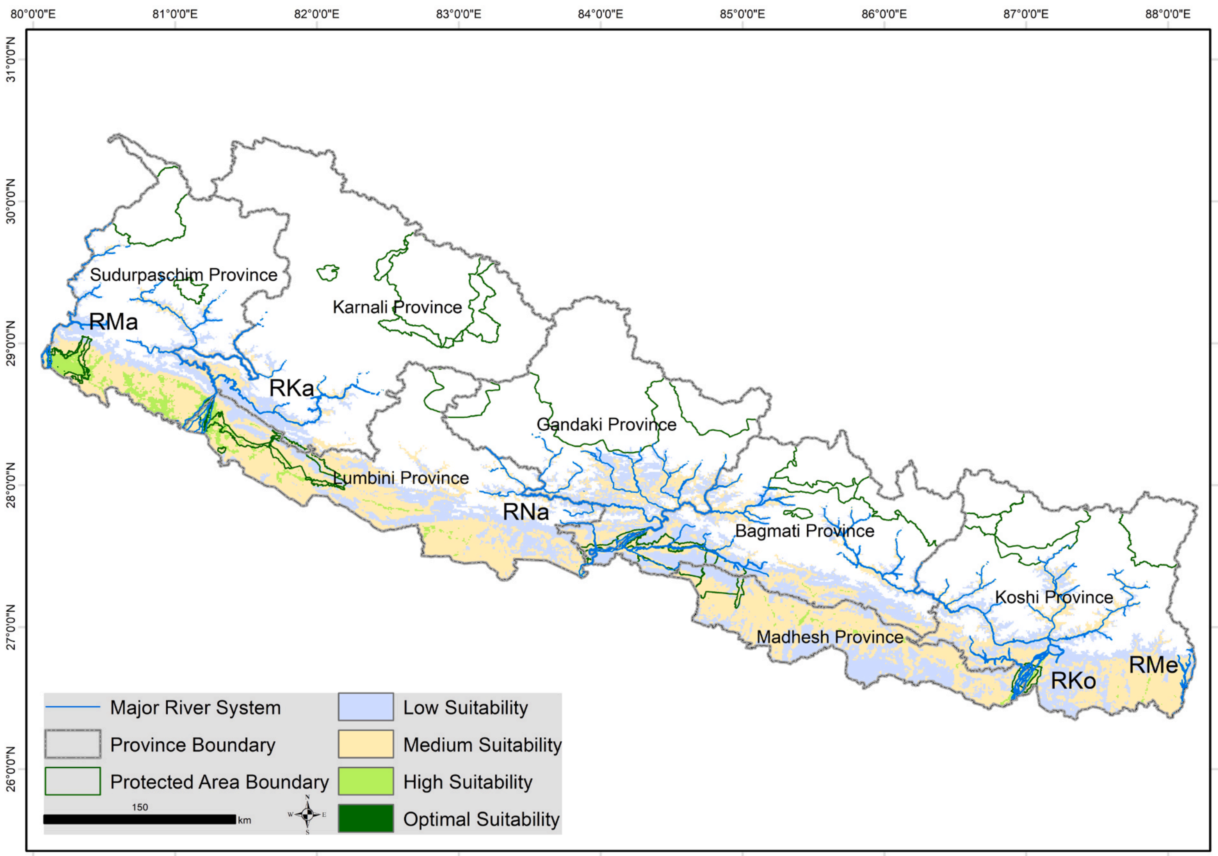

Fig. 3. Predicted suitable habitats of smooth-coated otters in Nepal by the ensemble model after application of the presence/absence threshold.

Table 3
Predicted potential area of suitable habitat for smooth-coated otters at the provincial level in Nepal, based on ensemble of small models. Number in parentheses represents km^2 in the category.

Province	Low suitability (%)	Medium suitability (%)	High suitability (%)	Optimal suitability (%)
Koshi	42.01	56.65	1.34 (129)	0
Madhesh	41.25	56.99	1.76 (168)	0
Bagmati	55.36	43.15	1.49 (111)	0
Gandaki	46.33	53.17	0.50 (24)	0
Lumbini	32.77	61.57	5.18 (633)	0.48 (58)
Karnali	56.44	42.47	1.09 (27)	0
Sudurpaschim	31.21	48.46	19.82 (1190)	0.52 (31)

only a small portion (7.65%) of optimal suitability. Additionally, high suitability was found only in Bardia NP (40.82%) and Shulaphanta NP in western Nepal (30.77%). The percentage of largest amount of medium suitable habitat was found in Koshi Tappu Wildlife Reserve (79.73), followed by the Banke NP (70.20), Chitwan NP (66.63%), Shuklaphanta NP (65.89%) and Parsa NP (43.19%) (Table 4).

3.3. Landscape connectivity

The analysis identified 12 core areas with an average size of 142 km^2 (SD=200.64, range: 17.96–518.58 km^2) for the smooth-coated otter distributions in lowland Nepal. Similarly, a total of 14 direct linkages have the potential to connect the cores. The mean Euclidean distance was 61.9 km (SD=102.6). The average length of the LCP was 68.2 km (SD=111.9) and the cost-weighted distance was 4550.9 km (SD=7504). The ratio between LCP and CWD was 63.00 (SD=3.86) indicating the greater resistance to movement along the LCP in lowland Nepal on an average. Specifically, the linkage quality showed that the core areas between Mahakali and Karnali River systems was well connected, while the connectivity of core areas between the Narayani River and the Koshi River systems was fair. The quality of connectivity of multiple linkages between the Karnali and the Narayani varied from fair to poor (Fig. 4).

4. Discussion

4.1. Model performance and justification

This study calibrates a regional species distribution model to predict a potential distribution and geographic range for smooth-coated otters across Nepal and explores the effects of environmental variables in quantifying habitat suitability. Species distribution models with a limited number of presence points and many predictor variables lead to model overfitting (Guisan and Zimmermann, 2000). In the case of rare species with few and/or aggregated presence points, the ensemble of small models (ESMs) leads to avoiding a potential model over-fitting. Our approach of using ESM to predict the distribution, geographic range, and habitat suitability of smooth-coated otters in Nepal is justifiable. Having AUC value and Boyce's Index close to 1 indicates model consistency (Jiménez and Soberón, 2020) to predict smooth-coated otter distribution.

4.2. Distribution mapping and habitat suitability

The distribution of potential smooth-coated otter habitat was identified throughout the Terai region of Nepal, but was predicted to

Table 4
Habitat suitability values for smooth-coated otters in protected areas and associated buffer zone (BZ) of the lowland of Nepal. BNP = Bardia National Park; CNP = Chitwan National Park; BaNP = Banke National Park; PNP = Parsa National Park; ShNP = Shuklaphanta National Park; KTWR = Koshi Tappu Wildlife Reserve, KCA = Kanchanjunga Conservation Area.

Protected area	Low suitability (%)	Medium suitability (%)	High suitability (%)	Optimal suitability (%)
Bardia NP	41.95	44.25	10.49	3.31
Bardia BZ	1.79	49.74	40.82	7.65
Chitwan NP	57.63	35.61	6.76	0
Chitwan BZ	29.20	66.63	4.17	0
Banke NP	40.31	57.83	1.85	0
Banke BZ	26.41	70.20	3.39	0
Parsa NP	55.75	43.99	0.27	0
Parsa BZ	56.81	43.19	0	0
Shuklaphanta NP	4.07	10.75	82.15	3.04
BZ	3.34	65.89	30.77	0
Koshi Tappu WR	0	59.69	40.31	0
BZ	11.26	79.73	9.01	0
KCA	0	90.91	9.09	0

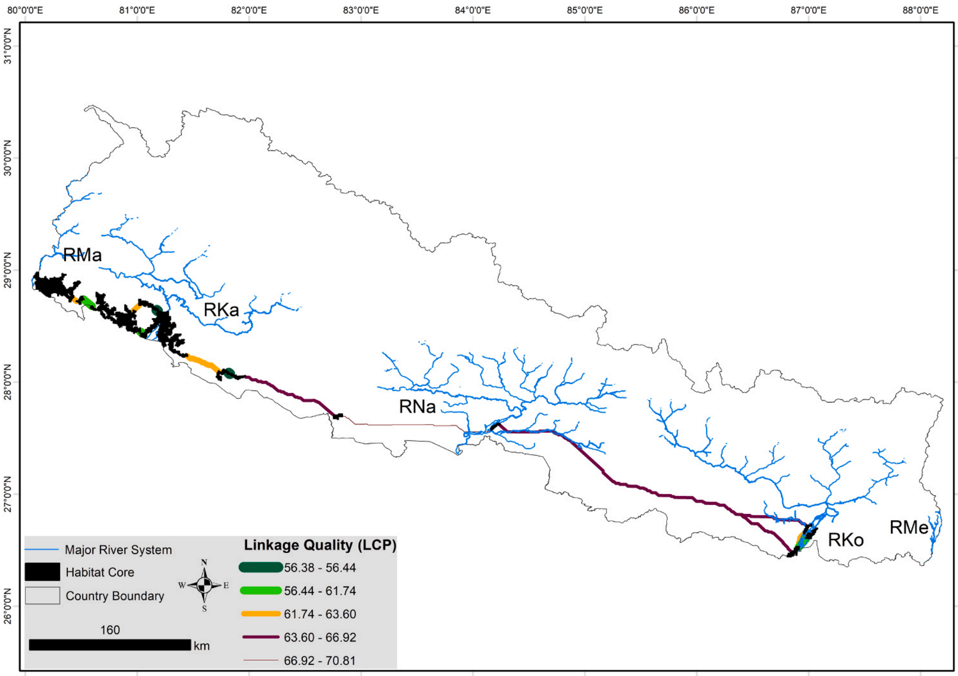

Fig. 4. Core habitats, potential linkages and linkage qualities identified for the smooth-coated otter in Nepal. Greener values indicate higher quality corridors, orange value represent fair quality corridors while purple and brown values indicate greater resistance for movement along the LCP.

be highly concentrated in protected areas, particularly in Bardia NP, Shuklaphanta NP and Koshi Tappu W*R* (Ramsar site) with total of 2374 km^2. However, site-specific evaluation helps to understand the viability of specific areas of habitat. Lowland areas of Nepal include a large number of freshwater wetlands, including permanent rivers, seasonal and irregular riverine floodplains, permanent freshwater lakes, seasonal freshwater lakes, permanent freshwater marshes and swamps, and aquaculture ponds. Sudurpaschim Province, followed by Lumbini Province, contain the majority of highly suitable habitat for smooth-coated otters in the region. In eastern Nepal, Koshi Tappu Wildlife Reserve has a large portion of medium suitable habitats, characterized by a large number of permanent, seasonal, and irregular rivers and floodplains, freshwater oxbow lakes, seasonally flooded grasslands, reservoirs and seasonally flooded rice fields.

The little or no availability of optimal suitability and high suitability habitats in all seven provinces may be pushing otters to use medium and low suitability areas. Thus, restoring smooth-coated otter habitat from the major rivers in lowland Terai would be beneficial for the survival of the species. An abundance of freshwater lakes might predict the habitat suitability for the species in Lumbini Province, since Parasi, Rupandehi, Kapilvastu, Dang, Banke, and Bardia Districts of Lumbini Province contain 21, 28, 24, 8, 6, and 3 freshwater lakes respectively (NLCDC, 2021). Additionally, the presence of a Jagdishpur Reservoir (Ramsar site), Karnali River Basin (Babai, Karnali, Geruwa, and Khauraha) in Bardia District could be considered as a potential habitat for smooth-coated otters.

The Sudurpaschim Province contains a large number of freshwater wetlands, including 47 freshwater lakes in Kailali and 26 in Kanchanpur districts (NLCDC, 2021), which contribute the second greater suitability for the species in the region. Specifically, Shuklaphanta NP contributes to greater habitat suitability for smooth-coated otters, since it contains the Mahakali and Chaudhar Rivers, many freshwater lakes (Rani Tal, Shikari Tal) along with dense coverage of grasslands and riparian vegetation.

The large number of lakes and ponds in the Terai particularly in Lumbini and Sudurpaschim Provinces have extensive farming of exotic carp species (common carp *Cyprinus carpio*, grass carp *Ctenopharyngodon idella*, silver carp *Hypophthalamichthys molitrix*) (Pandit and Rizal, 2022), and can provide important prey for otters, perhaps resulting in conflict with aquaculture farmers in the future. Appropriate mitigation measures to reduce conflict with otters should be developed in protected areas policies, forest policies, district fisheries policies and local government natural resources policies. Importantly, there is a need to focus on the protection of a wide range of habitats in Ramsar sites for enhancement of otter and wetland conservation (Brooks et al., 2011).

In our distribution and habitat suitability modeling, distance to water was the most important ecological variable in determining the distribution of smooth-coated otters in lowland Nepal. Prey species include fish and amphibians (Tiler et al., 1989; Nawab and Hussain, 2012; Basak et al., 2021) and thus are associated with the water distances (Aryal et al., 2020). Otters primarily hunt for fish in water, however availability of other prey species including frogs, crabs, and insects may determine their distribution (Anoop and Hussain, 2005). Kamjing et al. (2017) suggests that otter occupancy is positively associated with proportion of natural habitat and cover near traditional aquaculture ponds. Higher human disturbances in wetland areas, high rate of deforestation in the Terai, and conversion of natural wetland areas into cropland result in a shrinkage of suitable habitats for otters (Acharya, 2017). A study on another otter species Eurasian otter (*Lutra lutra*) in the United Kingdom also accords with our study, regarding water distances and prey species availability (Riley et al., 2020). A restored hydrological regime, besides offering a prey base, could increase the breeding success and prey availability for otter species (Kruuk and Moorhouse, 1991).

The significant contribution of NDVI in habitat suitability for smooth-coated otters emphasizes their preference for open canopy or open spaces rather than densely-covered canopy. Basak et al. (2021) also identifies a medium canopy opening is preferred by the species in riverine ecosystems of the Himalayan foothills in India. Medium to dense tree and ground canopy, on the other hand, are preferred by other otter species, including giant otters *Pteroneura brasiliensis* (Noonan et al., 2017), Eurasian otters *L. lutra* (Weinberger et al., 2019; Wang et al., 2021), and Southern river otters *Lontra provocax* (Fuentes and Arriagada, 2022). In the Terai's protected areas, the vegetation of riverine grasslands is dominated by wild sugarcane *Saccharum spontaneum*, hardy sugarcane *S. arundinaceum*, Asian reed *Phragmites vallatoria*, plume grass *Erianthus ravennae*, cotton wool grass *Imperata cylindrical,* and bushes of wild Jujube *Zizyphus rugosa*, which provide crucial shelter and resting site for otters. Thus, deforestation, changes in ground canopy, and conversion of riparian vegetation for settlements or agriculture can impact the habitat suitability for smooth-coated otters. Riparian vegetation along the riverine stretches also provides breeding sites for otters (Prenda, 1996). Weinberger et al. (2019) emphasized the restoration of riparian vegetation cover to provide crucial resting ground for otters in a human-dominated landscape.

Precipitation either in the driest month, warmest quarter, or driest quarter contributes to habitat suitability for smooth-coated otters in Nepal. Grasslands and riverine forest habitats, precipitation during the driest month provide high suitability for smooth-coated otters. Decrease of water levels in the river systems during the driest month, wetlands including oxbow lakes that are inter-connected with meandering river channels would be affected by such hydrological regime and river characteristics. Additionally, a decrease in water availability would also reduce the foraging ground for otters. Additionally, grasslands and riverine forest habitats are also connected with hydrological regimes, river characteristics that contribute positively to habitat suitability for smooth-coated otters. Precipitation during the warmest period (range between 800 mm and 900 mm) emerged as the most important variable for habitat suitability. Submersion of riparian areas and dense coverage of *Saccharum spontaneum* and *Imperata cylindrica* during this period may decrease the basking and grooming sites, but contributes to greater availability of hunting grounds with more fish and invertebrates (Acharya, 2017). An increase or decrease of seasonal precipitation from this optimal range could decrease the suitability of otter habitats.

Smooth-coated otters occupy specialized niches and even a slight decrease in predicted precipitation results in a loss in the suitable habitat area up to 25% (Jamwal et al., 2022). A study on *Lutra lutra* also predicted that grasslands and forest habitats with moderate precipitation during the driest month provide preferred environments (Jamwal et al., 2022). Thus, small changes in the climatic and land use variables could lead to altered habitat suitability for otters. Importantly, a vulnerability index predicts that smooth-coated otters will be negatively affected by climate change. An analysis of observed and perceived climatic changes showed that the pre-monsoon, monsoon, and winter precipitation has been decreasing in Nepal in recent years (Thapa and Dhulikhel, 2019), which may lead to decrease the suitability range for smooth-coated otters. Additionally, the Eastern and Central Nepal monsoon is projected to increase more than the monsoon of Western Nepal (NCVST, 2009), which may relate to changes in habitat suitability for smooth-coated otters highlighted in this study. Thus, mitigation measures to adapt to climatic and land use changes in the distribution range of the smooth-coated otter will be crucial to secure the survival of the species.

4.3. Landscape connectivity

The identification of suitable patch, connectivity, and the permeability of landscape is vital to ensure the long-term conservation of smooth-coated otters in river basins of Nepal (Cianfrani et al., 2010). Having 142 km^2 of an average size of core areas for smooth-coated otters in the lowland Nepal indicates that multiple groups of otters could be sustained in each patch because the home range (linear range length) of smooth-coated otter vary from 2.1 to 6.6 km^2 (17 km) for males and 2.1 – 2.7 km^2 (5.5 – 7.0 km) for females (Hussain et al., 2008). The average distances of LCP distance and Euclidean length of 68 km and 61 km indicate the dispersal distance could not be feasible in between core habitats if there are no stepping stones. The area in between Karnali River and Mahakali River systems harbors greater potential of linkages in the landscape with high permeability for the dispersal of otters. The landscape includes two protected areas (Bardia and Shuklaphanta National Parks), and freshwater wetlands and corridor forests (Basanta and Khata corridors). The area supports more core habitats with least fragmentation of aquatic habitats. The connectivity of core areas between Narayani River and the Koshi River shows permeable landscape matrix scattered or far away from core areas. However, other habitats share less permeability for otter dispersal. Evidence has been documented in Nepal where smooth-coated otters were also camera trapped in Sal forest in Bardia National Park (Acharya, 2016) that indicates their ability to travel in forest-river systems in the adjoining wetlands of the riparian forest area. However, a detailed study of habitat patch and connectivity is required to maintain the long-term population of otters in river basins of Nepal.

5. Study limitations

MaxEnt may underestimate the probability of occurrence of a species within areas of observed presence, while overestimating it in areas beyond the species' known extent of occurrence (Gomes et al., 2018). In this modeling effort, we used an ensemble of small models to avoid model over-fitting, since occurrence records of smooth-coated otters are low. Ecological niche modeling approaches reach limitations when confronted with a low number of presence points (Papeş and Gaubert, 2007). In this study, we used 14 environmental predictors and 124 presence points, in an ensemble of small models for predicting the distribution of vulnerable smooth-coated otters. We used presence point records from field surveys based on the presence of otter signs (e.g., tracks and scats), sightings, and camera trap images. The lack of absence data constitutes a major constraint to discrimination modeling techniques– a major limitation for modeling species with low presence points (Chefaoui and Lobo, 2008; Wisz and Guisan, 2009). Some authors suggest that random creation of pseudo-absences could be an appropriate strategy to overcome the limitations of presence-only data sets, increasing the number and accuracy of eligible modeling techniques (Elith et al., 2006; Chefaoui and Lobo, 2008). It is worth mentioning that attention must be given to the generation of pseudo-absences and the selection of environmental variables to avoid overfitting (Elith and Leathwick, 2009). It is well-known that several environmental predictors affect the distribution of otters (e.g., water quality, land use, and climate alterations (Cianfrani et al., 2018; Jamwal et al., 2022) but could not be used in the analysis due to insufficient data. Thus, further study should incorporate future land use and climate change scenarios as well as incorporating additional environmental variables. Additionally, this study has targeted to evaluate only the quality of least-cost path (LCP) in major river basins of Nepal in order to understand the permeability of the freshwater system for the dispersal of smooth-coated otters. Functional connectivity study is essential for the conservation of semi-aquatic vertebrates because isolated habitats restrict movement, limit dispersal and gene flow (Carranza et al., 2012; Looy et al., 2014; Dutta et al., 2016; Leoncini et al., 2023).

6. Conservation implications and conclusion

Smooth-coated otters are highly threatened in lowland Nepal by habitat loss and degradation and climate change. Unpredictability of changing climate conditions and increasing land use alterations suggests a further reduction of the distribution range of smooth-coated otters. Strategies for grasslands and forest management and tree and ground canopy maintenance in riverine stretches would be invaluable for expanding otter habitats and recovering local otter populations. Restoration of degraded wetlands and riverine habitats to meet the habitat requirements, linking core habitats in Shuklaphanta and Bardia NPs has great potential in supporting the long-term survival of otter populations in the river basins of western lowland Nepal. Developing effective conservation strategies and appropriate management interventions focused on wetlands, particularly in Lumbini and Sudurpaschim Provinces, can enhance these possibilities. The responses of resource managers to climate change based on current and future predictions of otter distributions could also minimize adverse effects on this important indicator species. In general, Nepal lacks an integration of otter conservation efforts with wetland management policies of protected areas, buffer zones, Ramsar sites and river basins, necessitating an incorporation of conservation measures into these management strategies.

Declaration of Competing Interest

All authors agree with the contents of the manuscript and its submission to the journal. No part of the manuscript has been published in any form elsewhere, nor has it been submitted in any variation to any other journals. There is neither financial support nor direct financial benefits to the authors resulting from publication. No institutional IRB or IUCC approvals were required for the completion of this research. No conflicts of interest occurred during the research or in the writing phase of this manuscript. There are no competing interests in the publication of this manuscript.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02578.

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