


Research

Need for structured conservation inputs: a geospatial approach for habitat prioritization to restrict disturbance regime in the protected areas of the Western Himalayan region

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Abstract

The population boom increases land-use requirements, and shrinking regions are available to preserve natural biodiversity. Unfortunately, scientific knowledge does not seem to have and might never get a correct solution to how much territory will be sufficient for satisfying the various biodiversity conservation goals. Prioritization of habitat, primarily for threatened species, is a critical management challenge. Habitat management efforts are gradually being performed over broader geographic regions, emphasizing the necessity of spatial and strategic prioritization. Habitat prioritization is a technique popular for identifying critical areas needing conservation initiatives. To develop a strategic conservation framework, key issues must be identified based on the ground knowledge and present land use status, which are difficult to gather for highly rough terrain areas. Incorporating spatial data sets thus helps to get the desired knowledge of the site on a large scale. This study used a grid-based multicriteria approach to create a spatial conservation management framework for the Rajaji-Corbett landscape (RCL) in Northern India. A grid-based prioritization assessment was conducted to identify priority areas for the RCL, keeping invasive species and fire as significant threats. The indicators or criteria were selected by looking at present vital concerns in the landscape. We took 20 indicators for our multicriteria assessment for landscape prioritization of RCL using 2 × 2 km grids for the evaluation and classified them according to low, medium, and high priority areas using Arc GIS Pro. The results identified 931 sq. km area of this landscape needs immediate management interventions where frequent fire incidents and presence of invasive species are high. RCL is well known for its biodiversity wealth and assemblage of various wildlife populations.

Keywords Spatial prioritization · Landscape management · Protected area · Tiger reserve · Spatial modelling

1 Introduction

Spatial prioritizing is a strategy for identifying priority regions for biodiversity conservation. It is a technical step in structured conservation programs [34, 43, 45]. Spatial prioritization incorporates spatial data on the habitats of species, land use characteristics, anthropogenic pressure, the effects and costs of conservation interventions, administrative constraints such as the availability of lands, and the present extent of protected areas [50]. Studies by Kujala et al. [34] identified the importance of these data sets on conservation prioritization. The lack of resources in

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conservation management initiatives restricts their implementations on a broad scale, which leads to the formation of systematic conservation planning using minimal resources [41, 52]. However, conservation planning approaches have evolved swiftly, and the lack of suitable data hinders their implementation [55]. The conservation strategy is critically dependent on geographical knowledge regarding the distribution of biodiversity [44, 47], current land use problems, and distribution of invasive species, which is inadequate for extremely rugged and inaccessible landscapes. Existing statistics are severely biased against the parts of the globe with the most biodiversity, the least developed protected area networks, and the highest levels of biodiversity loss, precisely the places in need of conservation strategy [55, 74].

As human domination over Earth's natural systems grows, the rate of biodiversity loss accelerates [56, 72]. The most successful and least expensive method of conserving is to keep native species in their natural habitats, where they have the highest probability of long-term survival. Conservation plans for fragmented or altered landscapes must emphasize places where populations are most likely to persist over time [8, 11, 42, 43]: typically, where a specific species' habitats are shared, of good quality, and near together [20, 21]. Even though this contextual message is universally understood, statistical multi-species applications to distinguish priority landscapes at the spatial scale of entire populations have been limited: for most species in most landscapes, there is insufficient ecological data, population parameters, or habitat distribution information to allow simulation modelling [66] or calculation of the landscape's capacity to support populations [21].

Species-level landscape conservation assessment has been studied globally using different techniques and statistical methods [1, 36, 37, 44, 45, 69]. Nowadays, the most used species conservation tools are Maxran, Zonation, Weighted overlay, etc. [36, 44–46, 69]. These approaches are helpful when concerning species-level conservation management. For landscape-level conservation planning, vast datasets are needed on present land use status, anthropogenic pressure, topographic characteristics, etc., which can act as biodiversity indicators or surrogates of the landscape [47, 48, 54, 68]. In today's era, spatial datasets have become widely accessible with the help of various satellites capturing data on Earth's surfaces every hour. USGS, SEDAC, NRSC, Bhuvan, Copernicus, and Open Land Map are popular websites that give free downloads of processed satellite images for spatial analysis, mapping, and visualization. These resources can be used for any spatial level of conservation planning with proper knowledge of the targeted area and conservation problems. Reddi et al. conducted a similar study in the Western Ghats in 2018, while Vasudeva et al. focused on the Central Indian landscape in 2022 [70]. Both studies underscored the efficacy of employing spatial data in extensive landscape conservation planning initiatives. Globally, scientists have undertaken numerous studies since 2000. Rodrigues and Brooks [63] stressed that although conservation management plans can be swiftly developed, a restricting factor in their application is the availability of sufficient data, as highlighted by Prendergast et al. in 1999 [53].

This study used a grid-based multicriteria approach to create a spatial conservation management framework for the Rajaji-Corbett landscape (RCL hereafter). The Rajaji-Corbett landscape lies in the lower Shivalik region of the Western Himalayas and also covers a vast part of the Terai Arc Landscape Complex and mainly consists of two tiger reserves, i.e., Rajaji Tiger Reserve (RTR) and Corbett Tiger Reserve (CTR). The RCL plays a significant role in conserving multiple wildlife species, especially Tigers, Asiatic elephants, and Leopards. We used a grid-based prioritization assessment to identify priority areas for the RCL, keeping invasive species and fire as significant threats. The indicators or criteria were selected by looking at present vital concerns in the landscape.

2 Methodology

2.1 Study area

The study was carried out in parts of the lower Shivalik Himalayas. The Shivalik Himalaya is also recognized as sub-Himalaya or the youngest mountain in India. The Shivalik landscape extends from the Indus basin to the Brahmaputra basin. This landscape significantly contributes to the biogeography of the Indian subcontinent because it carries traits of the Indo-Malayan and Palaearctic regions. A large portion of the landscape falls under the Indo-Gangetic Plains and harbors several endangered and endemic flora and fauna apart from the existing human habitations. Our focal study area includes the Rajaji Tiger Reserve (RTR), Corbett Tiger Reserve (CTR), Kotdwar Forest Division, Kalagarh Forest Division, and Lansdowne Forest Division (Fig. 1).

The focal study area is a major part of the Rajaji Corbett Tiger Conservation Unit. The Rajaji Corbett Tiger Conservation Unit (RCTCU, 7500 km²) is one of 11 Level-I Tiger Conservation Units (TCUs) established in India for long-term tiger conservation [11, 25, 26]. RTR (Rajaji TR, 820 km²) and CTR safeguard approximately one-third of this TCU (Corbett TR, 1286 km²). The remainder is reserve forest divided into numerous forest divisions. CTR contains a 521 km² national park, Sonanadi Wildlife Sanctuary (WLS, 302 km²), which was part of the Kalagarh forest division until 1987, and a 463 km² buffer formed by parts of the Kalagarh, Ramnagar, and Terai West forest divisions. The Ganges divides RTR into eastern (Chilla WLS) and western parts (Rajaji and Motichur WLSs). Under rising biotic stressors, the weak habitat link between the two sections, the Chilla-Motichur corridor [28, 55, 66], is fast eroding [27].

The landscape's administrative boundary is shared by six districts of the state of Uttarakhand. A major part of the landscape comes under the district of Pauri Garhwal. The North-West part of the landscape falls under the districts of Haridwar and Dehradun. The East portion of the landscape comes under the administration of the Nainital district. Small areas of the landscape share boundaries with Almora in the North-East and Udham Singh Nagar in the South-East. The landscape has an average human density of approximately 550 individuals per km², making it one of India's most populous regions [27, 39]. Population growth-driven agricultural area development has been in apparent conflict with forest management since the nineteenth century and, to some extent, today. Flint [15] offers a thorough overview of the forest-agricultural boundary structure for vast sections of this landscape from the Mughal period onwards. During colonial governance, increased demand for forest products (mainly timber) adds another layer of human pressure on the forests. As a result, several economically significant market towns developed [69]. Ramnagar, Kaladhungi, Haldwani, and Tanakpur in the bhabar region, Kashipur, Bazpur, Gadarpur, Lalkuan, Kichha, and Sitarganj in the terai regions were the key centers to appear. According to reports, the human population increased by 130 percent between 1881 and 1981 [14, 27].

The study area is home to about 6.9 million people (Census India, 2011) and is marked by different resource stresses on the ecosystem [4, 18]. Furthermore, several portions of this landscape are inhabited by Gujjars, a nomadic pastoralist community. Although some are still migratory, migrating to the Shivalik and bhabar tracts in the winter and returning to

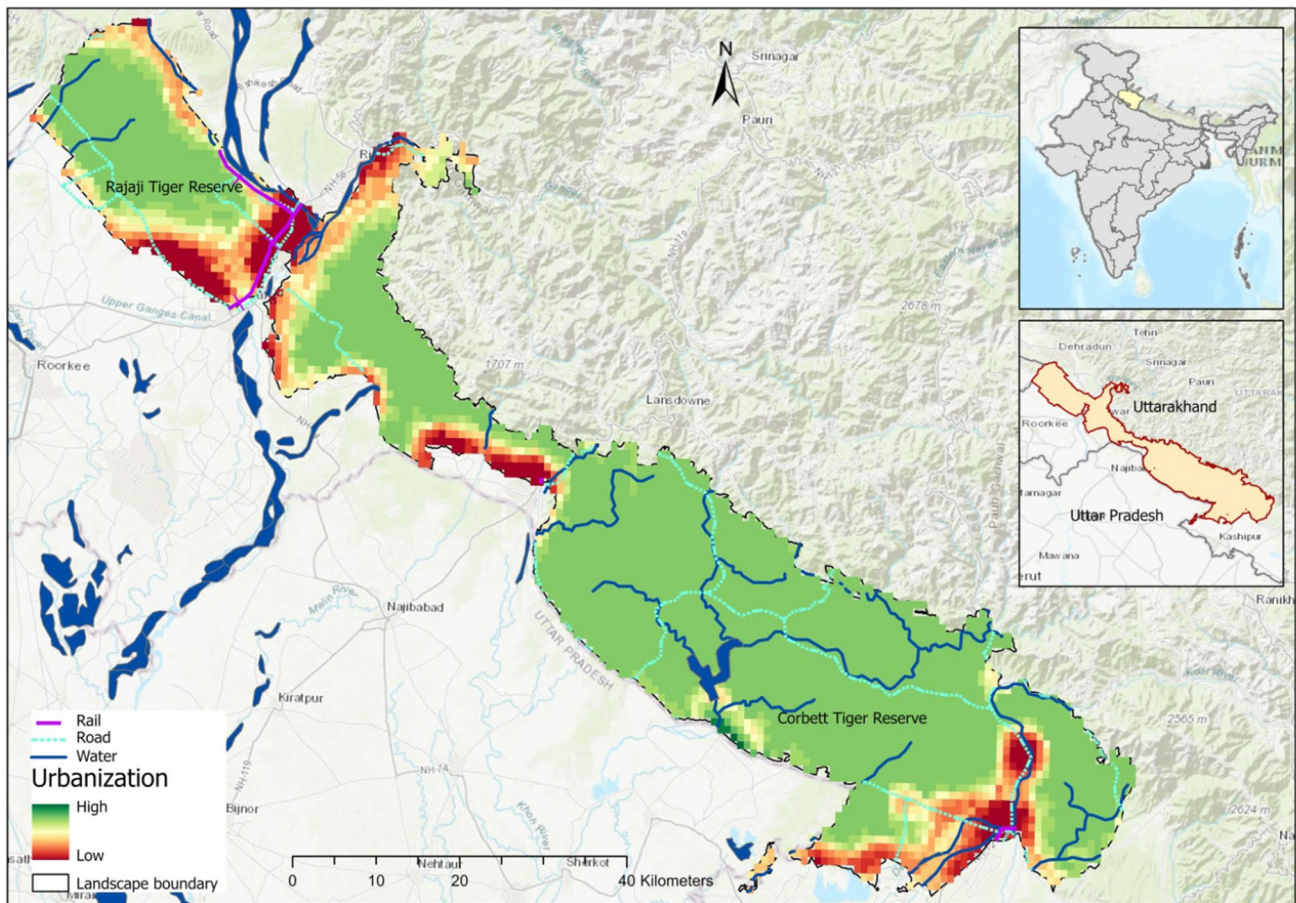


Fig. 1 Map of the study area

high-elevation pastures in the Himalayas in the summer, the vast majority live permanently inside these woods. Permits are provided to households who live in multiple-use woods to cut grass and clip branches off trees for leaves to feed their cattle. Such resource extraction is prohibited in the core areas of CTR and RTR. Their animal holdings, primarily buffaloes, are substantial, as are their feed requirements. Furthermore, growing urbanization in places like Dehradun, Haridwar, Kotdwar, Ramnagar, Haldwani, and Rudrapur, with a total population of 13,06,645 (Census data 2011) is separating already fragile corridors into fragmented areas [18, 19, 27].

This region's forest types are North Indian Deciduous forest (which includes moist shivalik sal forest), west gangetic moist mixed deciduous forest, Northern Tropical dry mixed deciduous forest, dry grassland, scrub, and dry bamboo bakes [9]. Sal (*Shorea robusta*) is the most dominant species in the area. It has floral elements of peninsular India. Several invasive species have been documented in studies from 2004 in this landscape [3, 10, 27, 49, 57, 58]. *Lantana camara* is the most dominant invasive species found across the landscape. *Sida spp*, *Agiratum conizoydis*, *Eupatorium spp* (Black and White) are some other invasives commonly found here. There are roughly 49 mammal species, 315 bird species, 49 reptiles, ten amphibians, and 49 piscine species in RTR, and 600 bird species, 50 mammals, 33 reptiles, 7 amphibians, two fishes, and 37 dragonfly species in CTR [30, 33].

2.2 Selection of spatial data

The selection of the criteria for conservation planning needs to be considered wisely. Before choosing the indicators, the conservation problems have to be addressed. Most conservation prioritization studies focused on species, but our approach was more habitats-specific concerning invasive species and fire presence in this study. So, we selected 20 indicators that characterize RCL in every aspect of topography, climate, influencing invasive species, and fire occurrence. The details of the spatial data used for the analysis are given below (Table 1):

Topography: Topography is one of the primary fundamental drivers of vegetation diversity. Scientists studied the effect of topographical changes on different ecological processes like micro refugia, in-situ speciation, forest fire, land use, etc. [24]. We downloaded the digital elevation model (DEM, SRTM) from the USGS website (<https://earthexplorer.usgs.gov/>) and processed it using our desired study area landscape extent in Arc GIS Pro. We used a spatial analysis tool in Arc GIS

Table 1 Details of the variables obtained for the present study

Variable details	Resolution	Description	Source
Bio2	1km	Mean Diurnal Range (Mean of monthly (max temp—min temp))	www.worldclim.org
Bio3	1km	Isothermality (8102/8107) (×100)	www.worldclim.org
Bio6	1km	Min Temperature of Coldest Month	www.worldclim.org
Bio8	1km	Mean Temperature of Wettest Quarter	www.worldclim.org
Bio15	1km	Precipitation Seasonality (Coefficient of Variation)	www.worldclim.org
Bio17	1km	Precipitation of Driest Quarter	www.worldclim.org
Bio18	1km	Precipitation of Wannest Quarter	www.worldclim.org
Bio19	1km	Precipitation of Coldest Quarter	www.worldclim.org
Bio13	1km	Precipitation of Wettest Month	www.worldclim.org
Slope	1km	Topographic characteristic	Digital elevation map.divagis
Aspect	1km	Topographic characteristic	Digital elevation map.divagis
Elevation	1km	Topographic characteristic	Digital elevation map.divagis
Topographic wetness	1km	Topographic characteristic	SEDAC
LULC modification	1km	13 anthropogenic pressures	SEDAC
NDVI	1km	Vegetation index	USGS, Landsat 8
Soil ph content at Ocm	1km	A measure of the acidity or alkalinity of the soil	Open land map.org
Soil carbon content at Ocm	1km	Solid terrestrial matter stored in soils	Open land map.org
Soil texture	1km	Characteristics of soil	Open land map.org
Lantana presence	1km	Disturbance factor	Distribution map of Lantana [49]
Forest fire intensity	1km	Disturbance factor	Fire intensity maps (fsi.gov.in)

Pro to get the slope, aspect, and elevation for RCL. Another topographic factor, topographic wetness, was downloaded from the SEDAC (<https://sedac.ciesin.columbia.edu/>) website and masked using RCL extent in Arc GIS Pro software (Fig. 2).

Soil characteristics: Soil contributes majorly to the sustenance of an ecosystem. Vegetation diversity, water level, propagations, and many more natural cycles depend on soil attributes. Thus, we considered soil parameters as one of our indicators for the analysis. Three soil parameters, namely, soil texture, soil pH, and soil carbon content, were used in the assessment [38, 65]. The data for all three parameters were downloaded from Open Land Map website (<https://openandmap.org/>). The data was downloaded for 0 cm depth and at 250 m resolution, and the desired extent was masked out in Arc GIS Pro (Fig. 2).

Climate: Changing climate conditions can have long-term effects on biodiversity and ecosystem processes. Studies have shown significant shreds of evidence on how rising temperatures can affect biodiversity [23], changes in rainfall patterns, extreme climatic conditions [22], extinction of species [75], increases in invasive species distributions [57], etc. We downloaded bioclimatic data from the Worldclim website (<https://www.worldclim.org/data/bioclim.html>). The data comes in the form of 19 layers, and each layer contains a specific climatic variable. We ran Pearson's multicollinearity test to eliminate the highly correlated variables and selected nine climatic indicators important for our analysis. The final variables were: mean diurnal range (mean of monthly (max temp – min temp) (bio 2), isothermality (bio 3), min temperature of the coldest month (bio 6), mean temperature of the wettest quarter (bio 8), precipitation of wettest month (bio 13), precipitation seasonality (bio 15), precipitation of driest quarter (bio 17), precipitation of warmest quarter (bio 18), and precipitation of coldest quarter (bio 19). All nine layers were masked out using the RCL boundary for analysis in Arc GIS Pro (Fig. 3).

Normalized difference vegetation index (NDVI): NDVI parameter is generally used to analyze the vegetation quality and distribution across regions [49, 57]. NDVI specifies values ranging from -1.0 to 1.0, with negative values created mainly by clouds, water, and snow and matters near zero formed explicitly by rocks and bare soil. The NDVI function's minimum values (0.1 or less) correspond to empty stones, sand, or snow expanses. Shrubs and meadows are

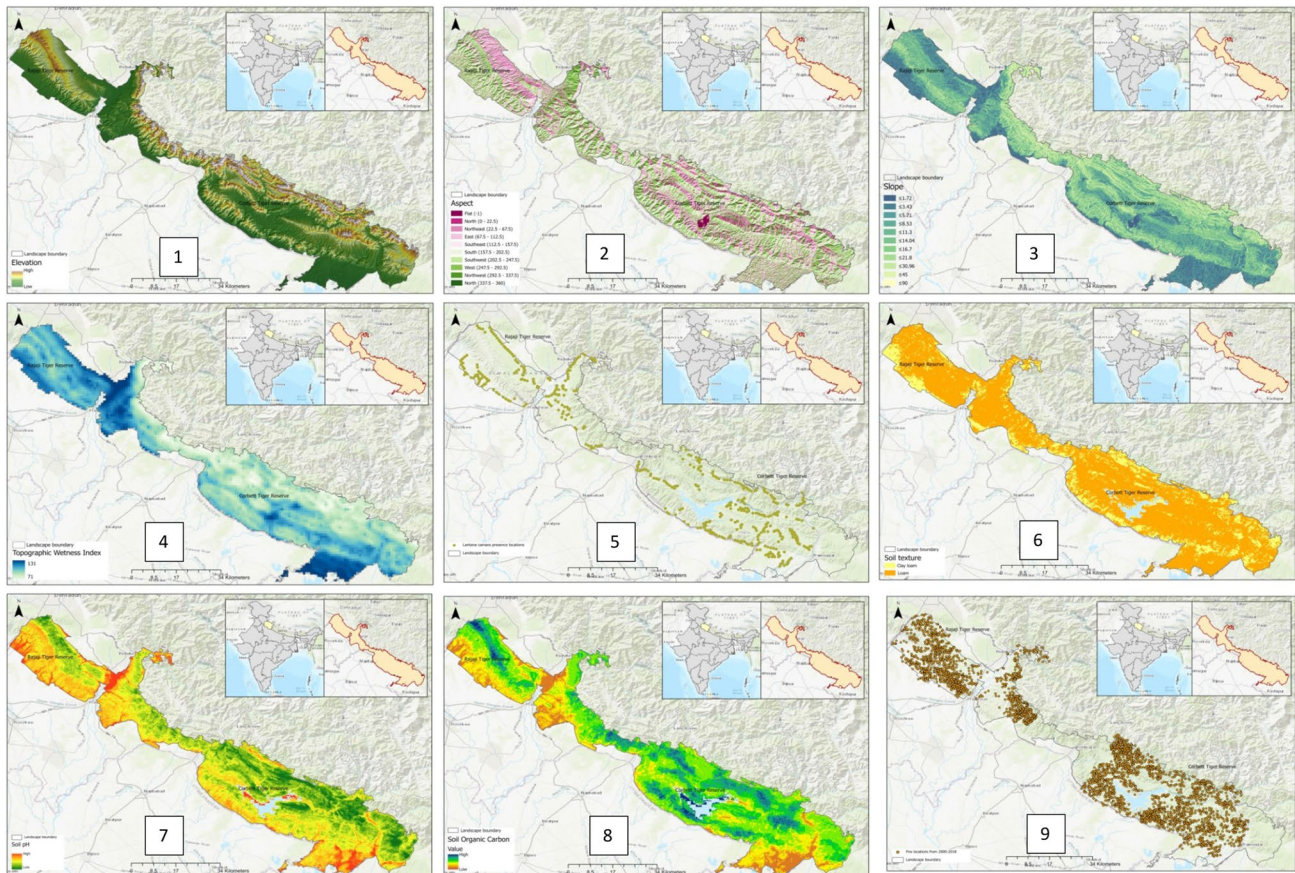


Fig. 2 Indicators used for the multicriteria analysis: 1—Elevation, 2—Aspect, 3—Slope, 4—Topographic wetness, 5—Lantana camara presence I, 6—Soil texture, 7—Soil pH, 8—Soil organic carbon, 9—Forest Fire locations

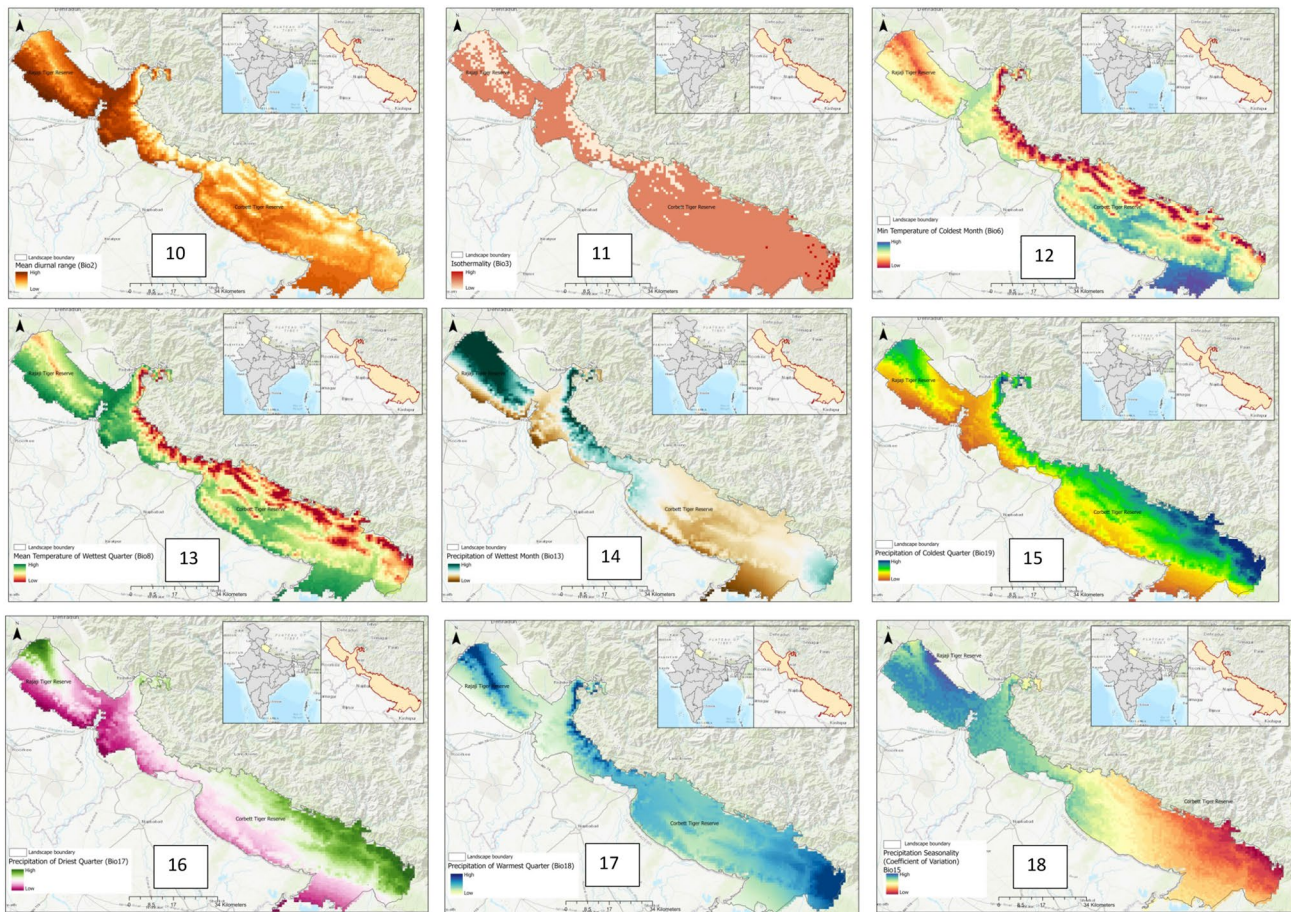


Fig. 3 Indicators used for the multicriteria analysis: 10—Bio2, 11—Bio3, 12—Bio6, 13—Bio8, 14—Bio13, 15—Bio19, 16—Bio17, 17—Bio18, 18—Bio15

represented by moderate values (0.2 to 0.3), whereas temperate and tropical forests are characterized by significant values (0.6 to 0.8). The NDVI value was calculated using Landsat 8 OLI satellite imagery (2018), downloaded from the USGS website (<https://earthexplorer.usgs.gov/>). The data was clipped using the RCL boundary, and for NDVI calculation, we used the indices tool in Arc GIS Pro software (Fig. 4).

Invasive species distribution: The presence of invasive species in biodiversity-rich habitats can create long-term effects on habitat loss, habitat degradation, native species propagation, etc. The invasive *Lantana camara* across the landscape dominates RCL. Several studies have been conducted on the distribution and management of this invader in this region [3, 49, 50, 58, 59]. We used the present potential distribution of this invasive from the published work of Mondal et al. 2022 [49] (Fig. 2).

Fire intensity: Forest fires in India burn about 34,000 ha of forested lands each year, destroying natural habitats, ecologically rich biodiversity areas, and endangered species habitats [35, 71]. The forest fire occurrence points were downloaded from the Forest Survey of India's Fire Alert System (<https://fsiforestfire.gov.in/>) portal. The data were sorted based on the availability of points in respective areas. For RTR 1046 and CTR 1860, occurrence points were considered for further analysis. The Kernel density tool in Arc GIS Pro software calculated fire intensity for RCL. The final fire intensity map was used for the analysis (Fig. 2).

Land use land cover: Land use land cover is an essential parameter as it describes the present conditions of the landscape in terms of areas of forested land, urban areas, cultivated regions, industrialization, etc. Before the conservation framework, this information is essential to gather and include in the management plan for mitigation measures. We used the Global Human Modification data set (gHM) from the SEDAC website. The gHM data set provides a cumulative measure of the human modification of terrestrial lands across the globe at a 1-km resolution, based on modelling the

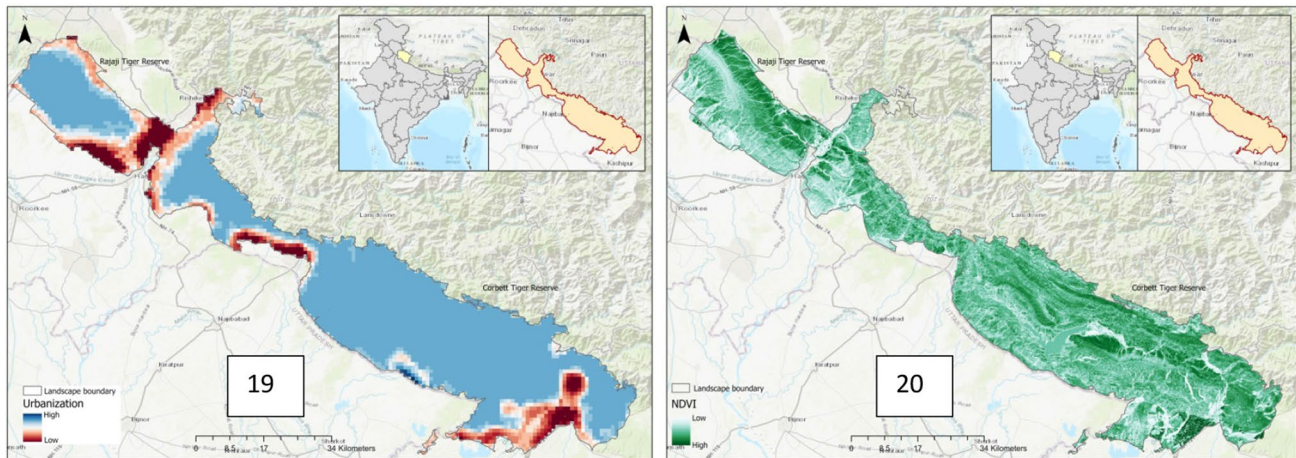


Fig. 4 Indicators used for the multicriteria analysis: 19—LULC modification, 20—NDVI

physical extents of 13 anthropogenic stressors and their estimated impacts [31]. The data were masked out using the RCL boundary for further processing (Fig. 5).

2.3 Grid-based multicriteria analysis

Multicriteria decision analysis is “a set of formal methodologies that strive to take explicit account of critical aspects in assisting people or groups in exploring important decisions” [4]. Multicriteria approaches have been applied to geographical issues for around 20 years by combining them with geographic information systems (GIS) [7, 40]. Multicriteria decision analysis assists decision-makers in evaluating future actions or alternatives based on different unmeasurable parameters, which are combined using decision rules to grade or rank the possibilities [12, 13, 41]. Although the multicriteria cannot always be maximized when choosing an alternative or action, academics and practitioners do not see it as merely a quantitative optimization issue determining the best potential solutions. Instead, the emphasis is on eliciting and applying the values and subjectivity to more objective metrics and comprehending the ramifications of these values and subjectivity [4, 62]. The discipline is frequently referred to as multiple criteria decision making, although decision analysis or ‘aiding’ more accurately represents the more delicate and complex aspects.

All the spatial layers for the analysis were rescaled into 1 km spatial resolution using Resample tool in Arc GIS Pro software. The rescaling of the layers was essential to extract values from them; uniformity cannot be maintained at different spatial scales. We used 863 grids of $2 \times 2 \text{ km}^2$ covering the RCL extent completely. The spatial tool Zonal statistics as table was utilized to extract values for each grid cell. Generally, this tool summarises the values of the target raster inside the desired grid area. The grid file was used to summarize the values for each cell for each indicator layer (pro.arcgis.com). The values for each grid cell were transformed into a 0–1 scale in Excel format. The final step is to combine all weights and rank them. The summation of all weight values for each grid was done using raster calculator in the spatial analyst tool [52, 64] (Fig. 7). The index results were then categorized using the symbology tool by selecting the quantile method and graduated color scheme in Arc GIS Pro (Fig. 6). The results were validated using the captured records of Tigers, Elephants, and Leopards in the RCL during the last tiger census program in the country [25] (Fig. 5).

3 Results

A grid-based multicriteria approach was taken to identify the high-priority areas in RCL where invasive species and repeated fire incidence majorly threaten the habitat. The overall calculated priority index ranges from 5–16 as low to high priority areas. In the low-priority area, 284 grids were identified, covering 926.7 sq. km area of the landscape. 286 grids fall under the moderate priority area, spreading across 994.76 sq. km of RCL. The high-priority grids cover 931.25 sq. km area and 285 grids (Fig. 6).

At the finer scale, we found that the western part of the RTR has major high-priority grids covering the Motichur, Haridwar, and Kansro ranges. Ranges like Ramgarh, Chillawali, Beribara, Chilla, Shyampur, Rawasan, Laldhang, and Kotdwar

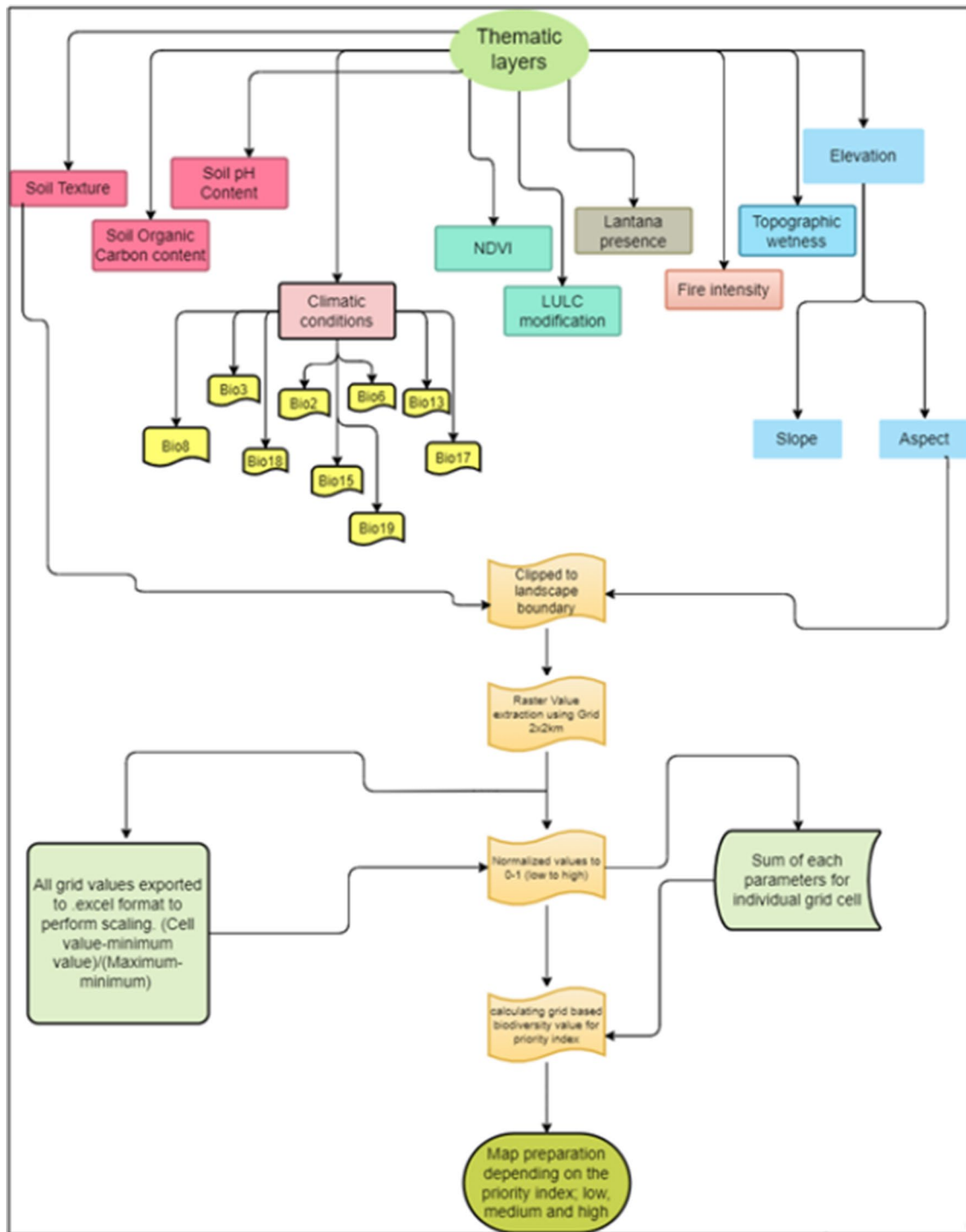


Fig. 5 Flowchart of the methodology obtained for multicriteria analysis

have lower high-priority grids and higher moderate-priority grids. The least high-priority grids were spotted in the Gohri range. In CTR, Kalagarh and Sonanadi have the most areas of high-priority grids. Mandal, Sarpduli, Dhikala, Jhirna, Bijrani, Dhela, Kota, Ramnagar, and Bailparao ranges have moderately spreading high-priority grids. Other ranges like Sand, Kotdi, Palain, Adnala, and Maidavarán mostly fall under low to moderate priority areas. We also observed that most of the high and medium-priority grids are significant habitats for Tigers and Elephants present within the ranges, namely, Motichur,

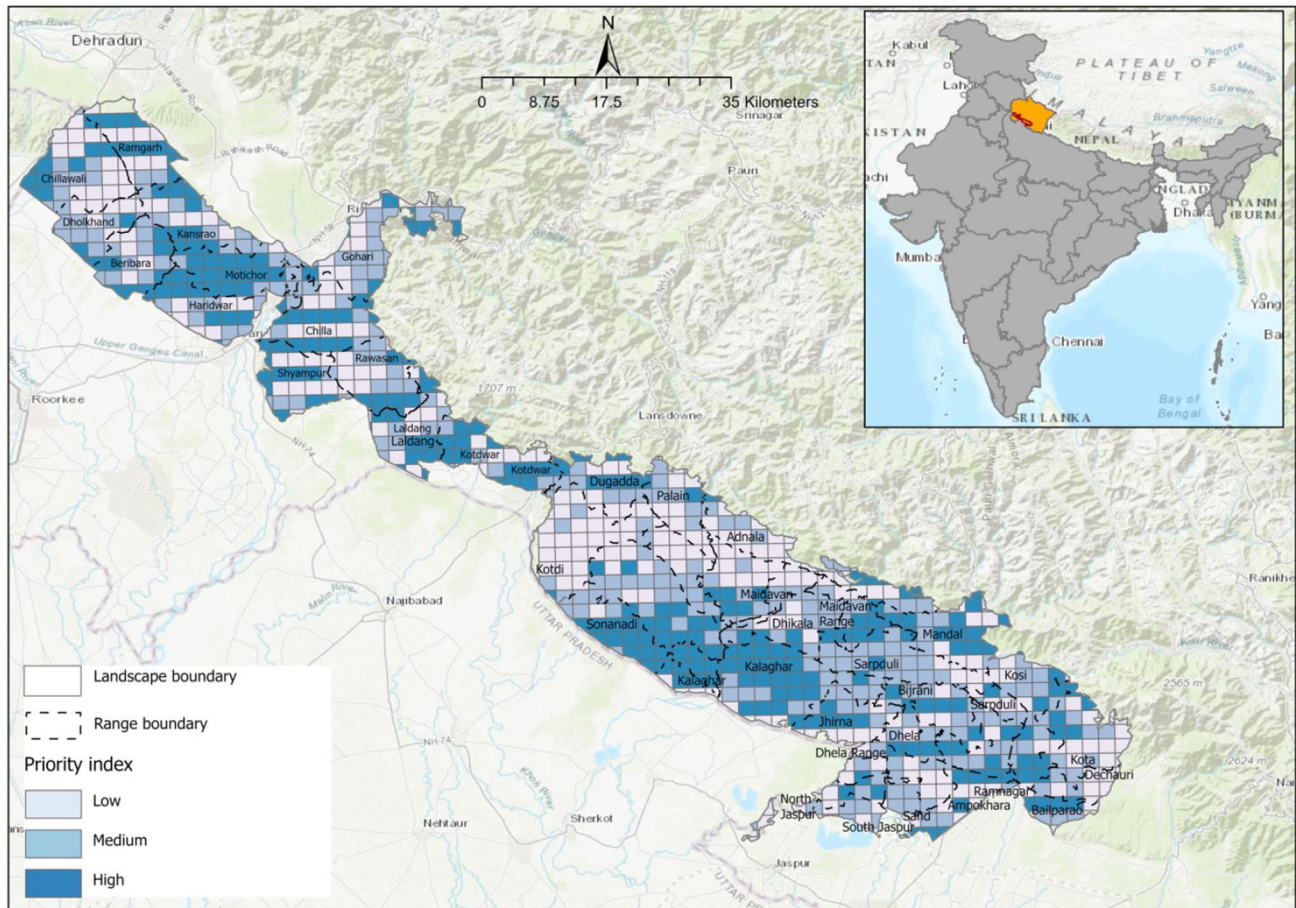


Fig. 6 Priority index map showing different priority classes across the landscape

Chilla, Sonanadi, Kalagarh, Dhikala, Jhirna, Bijrani, Dhela, Sarpduli, and Mandal. Leopard captures were mainly overlaid within the ranges' medium to low-priority grids, namely Lansdowne, Dugadda, Kosi, Kota, and Dechuri.

4 Discussion

The integration of multicriteria analysis for conservation planning at the landscape level is not an easy task. Landscape-level data is necessary for each criterion or indicator to go with this approach. The requirements should be selected by understanding the problem and implications of the outcome, which should be transparent [4, 62]. In this study, we took invasive species and fire occurrence as the most disturbing factors in the RCL. Our multicriteria analysis at the grid level identified the severely affected areas of the landscape. Grids that fall under the high-priority regions show a high presence of invasive species and incidents of forest fires, which validates our analysis's outcomes.

RCL is home to several large mammals, herbivores, birds, and aquatic animals. The landscape comes under the Terai Arc Landscape conservation area. The role of RCL in species conservation and wildlife habitat conservation is vital. According to the last tiger census [25], the whole RCL is a significant habitat for Tiger (*Panthera tigris*). Approximately 450 tiger individuals were identified during the survey here.

Furthermore, a significant area of RCL is also a part of the Shivalik Elephant Reserve, spreading across 5405 km². The state of Uttarakhand harbors approximately 1700 Asian Elephants (Uttarakhand Forest Department, 2015), mainly residing within the RTR and CTR. The studied landscape is also a critical part of the Rajaji-Corbett Tiger Conservation Unit in northwest India, which has been identified for long-term tiger conservation in India as a level-I tiger conservation unit [11, 29]. The geographical establishment of RCL is in the transit zone between the Himalayas and Terai plains;

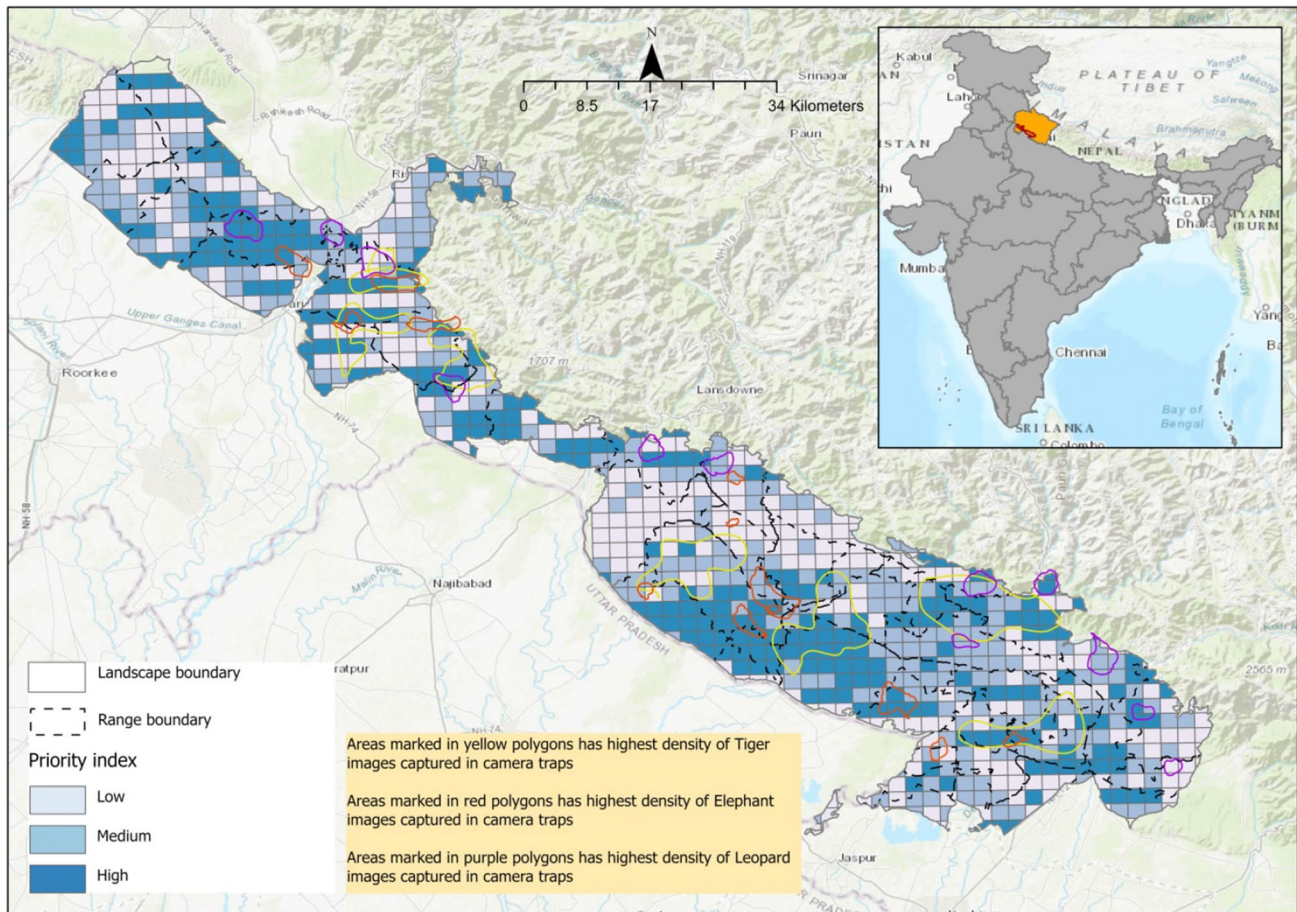


Fig. 7 Maps showing the overlapping of leopard, tiger and elephant movements within and outside of the high priority grids

species like Himalayan Yellow Throated Martin, Goral, Black bear, and many migratory bird species are also found here [25, 66]. A recent study reported the first record of Indian wolf (*Canis lupus pallipes*) from the western part of RTR [32]. Studies for the conservation of large carnivores and other associated mammals are frequently accomplished in RCL, which also concerns the conservation of this heterogeneous landscape habitat [19, 29, 30, 51, 66]. The spatial overlay of our results with the camera trap records of tiger census, 2018 [25] helped us to visualize the critical habitat areas where most tiger, elephant, and leopard pictures were captured (Fig. 7). Leopards and elephants are active in the far northwest area of the terrain (western half of RTR). The acquired regions lie under our high-priority grids (Motichur and Kansro ranges), with a few exceptions falling inside our medium-priority grids. Captures of tigers, elephants, and leopards in the Chilla range were comparably higher than in the other ranges of RTR, and the areas fall within the high to medium priority grids. The presence of tigers in CTR was captured in the Sonanadi, Kalagarh, Dhikala, Maidavan, Sarpduli, Bijrani, and Dhela ranges mostly come under the high priority grids apart from Sonanadi. Scattered capture of leopards in the buffer areas of CTR was observed within the medium priority grids.

This research endeavors to establish a comprehensive framework for landscape-level conservation management that can serve as a replicable model across diverse geographical contexts. The effective implementation of conservation management plans often requires substantial resources, and the unavailability of funds can impede the seamless execution of strategies in the field. A strategic grid-based framework proves advantageous in calculating the cost per unit area, providing a tangible assessment of resource requirements in high-risk areas. This approach empowers park managers to strategically plan and allocate funds based on identified risk factors, facilitating a more targeted and efficient implementation of conservation strategies.

4.1 Conservation management inputs

The methodology employed in this study successfully achieved the study's objectives, particularly in enhancing the future conservation planning of the area. By refining the analysis to a significantly finer scale, the study output effectively pinpointed the most threatened landscape areas, emphasizing the critical need for immediate management intervention. In the realm of global environmental challenges, the proliferation of invasive species poses a substantial threat to natural ecosystems. While various attempts to control their spread have been explored by scientists, a universally proven scientific method remains elusive [3, 50, 57, 70].

Moreover, the escalating impact of global climate change, manifested in heightened temperatures leading to increased forest fires, presents a formidable challenge to ecologically rich habitats [2, 5, 6, 16]. Notably, recent catastrophic forest fires in Australia underscore the magnitude of destruction that can occur. However, the implementation of a robust scientific management framework has the potential to mitigate the adverse effects of invasive species and forest fires on habitat degradation.

While previous studies in the RCL landscape have predominantly focused on species conservation and connectivity of corridors between RTR and CTR [28, 30, 39, 67], a notable gap existed in adopting a large-scale landscape-level approach to conservation planning. This study illuminates the urgency for such assessments and precisely identifies areas where park managers should concentrate their efforts. By targeting the control of invasive species and minimizing the occurrence of forest fires, the study underscores the significance of protecting natural habitats and biodiversity on a landscape scale. After analyzing the outcomes of this study, the following management inputs are suggested for the RCL:

For *Lantana camara* management:

1. Eradication of invasive species (*Lantana camara*) must be repeated yearly without any gap, especially within high-priority areas. The marked range officers can take charge of monitoring the process.
2. Seeds of native plant species like *Terminalia alata*, *Ziziphus moretiana*, *Aegle marmelos*, *Syzygium cumini* etc., need to be augmented across the eradicated areas after every removal season.
3. The invasive plant's eradicated stems must be relocated completely from the eradication sites. *Lantana's* propagation process is intense and can thrive from a single remaining shoot.
4. A few areas of the western part of RTR, Laldhang, and Kotdwar are covered by *Agyratum conyzoidis* instead of *Lantana camara* surrounding the roads. This phenomenon is known as invasive competitiveness. Though the presence of *Agyratum* is restricting the movement of *Lantana*, the authorities need to monitor both spreads continuously.
5. Lansdowne, Kotdwar, Shyampur, Dhela, and Jhirna ranges face immense anthropogenic pressure. Logging, lopping, and grazing within the park boundaries make the habitat vulnerable to invasion.
6. CTR welcomes high tourist flow throughout the year. Tourist vehicles rush behind one another to give them the blink of a tiger in the lust for a good amount of tip. This creates immense pressure on the habitat and disturbs the wildlife present nearby. CTR authority should look into this matter and control the vehicle activities strictly.

For forest fire management:

1. Forest fires in RCL are commonly seen around March to May every year. The most devastating forest fire happened in 2016, the most devastating in the past eighteen years. Most parts of RTR are not accessible to natural water sources. Our analysis marked the most affected areas of RCL where most fire incidences happened. Daily patrolling in the identified ranges in the fire season should be done for early detection.
2. During fire seasons, animals migrate toward the areas where continuous water sources are available. RTR authorities recently installed water wholes throughout the reserve, frequently capturing animals around them. It was a remarkable step taken by the park authority. The presence of water in nearby areas will help the forest staff during massive fire occurrences. The forest staff works day and night to control the fire without much access to food and water. The water supply in these water holes during fire seasons must be monitored regularly.
3. Post-fire assessment in the most affected areas needs to be conducted to get proper knowledge of the present habitat status of the area, species loss, etc.
4. Integration of UAV technology will help detect fires in an early stage. Park authorities should include this technology as a daily patrolling system.

5. Monitoring the Forest Survey of India's live fire detection system will give data on the areas where immediate focus is needed.

5 Conclusion

Remote sensing techniques have recently been widely used to capture data that may be acquired at many spatiotemporal scales [61]. Remotely sensed imagery-derived environmental variables and indicators can give unique information on landscape parameters like changes in the spatial and temporal scales [73]. In the last several decades, satellite-derived indices such as topography, land cover, and vegetation (vegetation productivity) have been used for landscape management initiatives [60, 70]. These investigations revealed that with adequate data, GIS-based spatial conservation planning could be done with high accuracy (sometimes more significant than 90%). A GIS-based method combined with multicriteria analysis can be reliable in determining the habitat risk and developing an operational management plan at a finer scale. GIS-based multicriteria analysis facilitates calculating and analyzing spatial criteria like distance, topographical layers, climatic layers, etc. The multicriteria method for spatial-scale conservation problems can be visualized and identified [17].

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Declarations

Competing interests The corresponding author confirms on behalf of all authors that there have been no involvements that might raise the question of bias in the work reported or in the conclusions, implications, or opinions stated.

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References

1. Akçakaya HR, Sjögren-Gulve P. Population viability analyses in conservation planning: an overview. *Ecol Bull.* 2000;1:9–21.
2. Babu KV, Roy SA, Prasad PR. Forest fire risk modeling in Uttarakhand Himalaya using TERRA satellite datasets. *Eur J Remote Sens.* 2016;49(1):381–95.
3. Babu S, Love A, Babu CR. Ecological restoration of lantana-invaded landscapes in Corbett Tiger Reserve, India. *Ecol Restor.* 2009;27(4):467–77.
4. Belton V, Stewart T. Multiple criteria decision analysis: an integrated approach. Cham: Springer Science & Business Media; 2002.
5. Berkes F, Folke C. Linking social 500 and ecological systems for resilience and sustainability. Linking social and ecological systems: management practices and social mechanisms for building resilience. 1998; 1(4): 4.
6. Bhandari BS, Mehta JP, Semwal RL. Forest fire in Uttarakhand Himalaya: an overview. *Glimpses of Forestry Research in the Indian Himalayan Region.* GB Pant Institute of Himalayan Environment and Development, Almora. 2012; 167–176.
7. Cabeza M, Moilanen A. Design of reserve networks and the persistence of biodiversity. *Trends Ecol Evol.* 2001;16(5):242–8.
8. Carver SJ. Integrating multi-criteria evaluation with geographical information systems. *Int J Geogr Inf Syst.* 1991;5(3):321–39.
9. Champion HG, Seth SK. A revised survey of the forest types of India. Manager of publications. 1968.

10. D'Alessandro ANTONINO. Rajaji Tiger Reserve: conservation opportunities and challenges. *Curr Sci.* 2016; 110(6): 959.
11. Dinerstein E, Bolze DA. A framework for identifying high priority areas and actions for the conservation of tigers in the wild. *World Wildlife Fund-US*; 1997.
12. Eastman JR. IDRISI Taiga guide to GIS and image processing. Worcester, MA: Clark Labs Clark University; 2009.
13. Figueira J, Greco S, Ehtagott M. State of the art surveys. In *Multiple criteria decision analysis*. Springer. 2005.
14. Flint EP. Deforestation and land use in northern India with a focus on sal (*Shorea Robusta*) forests. In: Grove RH, Damodaran V, Satpal S, editors. *Nature and the orient: the environmental history of south and southeast Asia*. New Delhi: Oxford University Press; 1998. p. 421–58.
15. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 219–230, 78.
16. Gupta S, Roy A, Bhavsar D, Kala R, Singh S, Kumar AS. Forest fire burnt area assessment in the biodiversity rich regions using geospatial technology: Uttarakhand Forest Fire event 2016. *J Indian Soc Rem Sens.* 2018;46(6):945–55.
17. Greene R, Devillers R, Luther JE, Eddy BG. GIS-based multiple-criteria decision analysis. *Geogr Compass.* 2011;5(6):412–32.
18. Harihar A, Pandav B. Influence of connectivity, wild prey and disturbance on occupancy of tigers in the human-dominated western Terai Arc Landscape. *PLoS ONE.* 2012;7(7): e40105.
19. Harihar A, Pandav B, Goyal SP. Responses of tiger (*Panthera tigris*) and their prey to removal of anthropogenic influences in Rajaji National Park, India. *Eur J Wildl Res.* 2009;55(2):97–105.
20. Hanski I. Metapopulation dynamics. *Nature.* 1998;396(6706):41–9.
21. Hanski I, Ovaskainen O. The metapopulation capacity of a fragmented landscape. *Nature.* 2000;404(6779):755–8.
22. IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Brondízio ES, Settele J, Díaz S, Ngo HT, editors. Bonn, Germany: IPBES secretariat. 2019. p. 1–1082.
23. IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
24. Irl SD, Harter DE, Steinbauer MJ, Gallego Puyol D, Fernández-Palacios JM, Jentsch A, Beierkuhnlein C. Climate vs topography–spatial patterns of plant species diversity and endemism on a high-elevation island. *J Ecol.* 2015;103(6):1621–33.
25. Jhala YV, Qureshi Q, Nayak A. Status of tigers, copredators and prey in India, 2018. National Tiger Conservation Authority, Government of India, New Delhi, and Wildlife Institute of India, Dehradun. 2020.
26. Jhala YV, Qureshi Q, Nayak A. Status of tigers, copredators and prey in India, 2014. National Tiger Conservation Authority, Government of India, New Delhi, and Wildlife Institute of India, Dehradun. 2020.
27. Johnsingh AJT, Negi AS. Status of tiger and leopard in Rajaji-Corbett Conservation Unit, northern India. *Biol Cons.* 2003;111(3):385–93.
28. Johnsingh AJT, Prasad SN, Goyal SP. Conservation status of the Chila-Motichur corridor for elephant movement in Rajaji-Corbett National Parks area, India. *Biol Conserv.* 1990;51(2):125–38.
29. Joshi R. Status and conservation of Asian Elephant in Rajaji National Park, North India: a review on a decade of research on elephant's behavior and ecology. 2017.
30. Joshi R, Singh R, Dixit A, Agarwal R, Negi MS, Pandey N, Pushola R, Rawat S. Is isolation of protected habitats the prime conservation concern for endangered Asian elephants in Shivalik landscape. *GJESM.* 2010;4(2):113–26.
31. Kennedy CM, Oakleaf JR, Theobald DM, Baruch-Mordo S, Kiesecker J. Documentation for the global human modification of terrestrial systems. NASA Socioeconomic Data and Applications Center (SEDAC): Palisades, NY, USA. 2020.
32. Krishna A, Mondol S, Lyngdoh S. First photographic record of Indian wolf in Rajaji Tiger Reserve, Uttarakhand, North India. *Canid Biol Conserv.* 2022;24(4):17–20.
33. Kukkala AS, Moilanen A. Core concepts of spatial prioritisation in systematic conservation planning. *Biol Rev.* 2013;88(2):443–64.
34. Kujala H, Moilanen A, Gordon A. Spatial characteristics of species distributions as drivers in conservation prioritization. *Methods Ecol Evol.* 2018;9(4):1121–32.
35. Kunwar RM, Khaling S. Forest fire in the Terai, Nepal: causes and community management interventions. *Int For Fire News.* 2006;34:46–54.
36. Lehtomäki J, Moilanen A. Methods and workflow for spatial conservation prioritization using Zonation. *Environ Model Softw.* 2013;1(47):128–37.
37. Mallory CD, Boyce MS. Prioritization of landscape connectivity for the conservation of Peary caribou. *Ecol Evol.* 2019;9(4):2189–205.
38. Mandal G, Joshi SP. The role of habitat types and soil physicochemical properties in the spread of a non-native shrub *L. camara camara* in the Doon valley, Western Himalaya India. *J Environ Geogr.* 2014;7(3–4):31–42.
39. Malviya M, Ramesh K. Human–felid conflict in corridor habitats. *Hum-Wildl Interact.* 2015;9(1):48–57.
40. Malczewski J. GIS-based multicriteria decision analysis: a survey of the literature. *Int J Geogr Inf Sci.* 2006;20(7):703–26.
41. Malczewski J. GIS and multicriteria decision analysis. New York: Wiley; 1999.
42. Margules CR, Sarkar S. Systematic conservation planning. 1st ed. Cambridge: Cambridge University Press; 2007.
43. Margules CR, Pressey RL. Systematic conservation planning. *Nature.* 2000;405(6783):243–53.
44. McIntosh EJ, Chapman S, Kearney SG, Williams B, Althor G, Thorn JP, et al. Absence of evidence for the conservation outcomes of systematic conservation planning around the globe: a systematic map. *Environ Evid.* 2018;7(1):1–23.
45. Mendoza-Ponce AV, Corona-Núñez RO, Kraxner F, Estrada F. Spatial prioritization for biodiversity conservation in a megadiverse country. *Anthropocene.* 2020;1(32): 100267.
46. Moilanen A, Lehtinen P, Kohonen I, Jalkanen J, Virtanen EA, Kujala H. Novel methods for spatial prioritization with applications in conservation, land use planning and ecological impact avoidance. *Methods Ecol Evol.* 2022;13(5):1062–72.
47. Moilanen A. Spatial conservation prioritization in data-poor areas of the world. *Nat Conserv.* 2012;10:1219.
48. Moilanen A, Arponen A. Administrative regions in conservation: balancing local priorities with regional to global preferences in spatial planning. *Biol Cons.* 2011;144(5):1719–25.
49. Mondal T, Bhatt D, Ramesh K. Bioclimatic modelling of *Lantana camara* invasion in the Shivalik landscape of Western Himalaya. *Trop Ecol.* 2023;64(2):249–63.

50. Mungi NA, Qureshi Q, Jhala YV. Expanding niche and degrading forests: Key to the successful global invasion of *Lantana camara* (sensu lato). *Glob Ecol Conserv*. 2020;1(23): e01080.
51. Nandy S, Kushwaha SP, Mukhopadhyay S. Monitoring the Chilla-Motichur wildlife corridor using geospatial tools. *J Nat Conserv*. 2007;15(4):237–44.
52. Nyerges TL, Jankowski P. *Regional and urban GIS: a decision support approach*. Guilford Press; 2009.
53. Pressey RL, Humphries CJ, Margules CR, Vane-Wright RI, Williams PH. Beyond opportunism: key principles for systematic reserve selection. *Trends Ecol Evol*. 1993;8(4):124–8.
54. Prendergast JR, Quinn RM, Lawton JH. The gaps between theory and practice in selecting nature reserves. *Conserv Biol*. 1999;13(3):484–92.
55. Pimm SL, Lawton JH. Planning for biodiversity. *Science*. 1998;279(5359):2068–9.
56. Pimm SL, Russell GJ, Gittleman JL, Brooks TM. The future of biodiversity. *Science*. 1995;269(5222):347–50.
57. Priyanka N, Joshi P. Modeling spatial distribution of *Lantana camara*—a comparative study. *Can J Basic Appl Sci*. 2013;1:100–17.
58. Ramaswami G, Kaushik M, Prasad S, Sukumar R, Westcott D. Dispersal by generalist frugivores affects management of an invasive plant. *Biotropica*. 2016;48(5):638–44.
59. Riley KL, Steelman T, Salicrup DR, Brown S, Hood SM, Drury S, Steelman T, Steffens R. On the need for inclusivity and diversity in the wild-land fire professions. In *Proceedings of the Fire Continuum Conference—Preparing for the future of wildland fire*. 2018, pp. 21–24.
60. Rocchini D, Luque S, Pettorelli N, Bastin L, Doktor D, Faedi N, Feilhauer H, Féret JB, Foody GM, Gavish Y, Godinho S. Measuring β -diversity by remote sensing: a challenge for biodiversity monitoring. *Methods Ecol Evol*. 2018;9(8):1787–98.
61. Roy PS, Roy A, Joshi PK, Kale MP, Srivastava VK, Srivastava SK, Dwevidi RS, Joshi C, Behera MD, Meiyappan P, Sharma Y. Development of decadal (1985–1995–2005) land use and land cover database for India. *Rem Sens*. 2015;7(3):2401–30.
62. Roy B. Paradigms and challenges. *Multiple criteria decision analysis: State Art Surv*. 2016:19–39.
63. Rodrigues AS, Brooks TM. Shortcuts for biodiversity conservation planning: the effectiveness of surrogates. *Annu Rev Ecol Evol Syst*. 2007;38:713–37.
64. Setiawan I, Mahmud AR, Mansor S, Mohamed Shariff AR, Nuruddin AA. GIS-grid-based and multi-criteria analysis for identifying and mapping peat swamp forest fire hazard in Pahang, Malaysia. *Disaster Prev Manag Int J*. 2004;13(5):379–86.
65. Sharma GP, Raghubanshi AS. *L. camara* invasion alters soil nitrogen pools and processes in the tropical dry deciduous forest of India. *Appl Soil Ecol*. 2009;42(2):134–40.
66. Sivakumar K, Sathyakumar S, Rawat GS. A preliminary review on conservation status of Shivalik landscape in Northwest, India. *Indian For*. 2010;136(10):1376.
67. Sjogren-Gulve P, Ebenhard T. *The use of PVA in conservation planning*. 2000.
68. Tucker R. Non-timber forest products policy in the Western Himalaya. In: Grove RH, Damodaran V, Satpal S, editors. *Nature and the Orient: the environmental history of South and Southeast Asia*. New Delhi: Oxford University Press; 1998. p. 459–83.
69. Vasudeva V, Upgupta S, Singh A, Sherwani N, Dutta S, Rajaraman R, Chaudhuri S, Verma S, Johnson JA, Krishnamurthy R. Conservation prioritization in a tiger landscape: is umbrella species enough? *Land*. 2022;11(3):371.
70. Verma AK, Kaliyathan NN, Bisht NS. Forest fire prediction modeling in the Terai Arc landscape of the lesser Himalayas using the maximum entropy method. *US Forest Service RMRS P-78*. 2020.
71. Vitousek PM, Mooney HA, Lubchenco J, Melillo JM. Human domination of Earth's ecosystems. *Science*. 1997;277(5325):494–9.
72. Wang R, Gamon JA. Remote sensing of terrestrial plant biodiversity. *Remote Sens Environ*. 2019;15(231): 111218.
73. Williams P, Faith D, Manne L, Sechrest W, Preston C. Complementarity analysis: mapping the performance of surrogates for biodiversity. *Biol Cons*. 2006;128(2):253–64.
74. Williams NS, McDonnell MJ, Seager EJ. Factors influencing the loss of an endangered ecosystem in an urbanising landscape: a case study of native grasslands from Melbourne, Australia. *Landsc Urban Plann*. 2005;71(1):35–49.
75. WWF. *Living Planet Report 2020 - Bending the curve of biodiversity loss*. In: Almond REA, Grooten M, Petersen T, editors. Switzerland: WWF, Gland. 2020.

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