Predictive modelling and spatial prioritization of critical habitat availability for the vultures in the Greater Panna Landscape, India

Abstract

Vultures are a specialized species group, utilizing wide habitat and forage niches and their long-term survival depends on the protection of their critical habitats. Taking a landscape approach, we modelled the distribution of nest sites (n = 30) and roost sites (n = 31) of cliff-nesting vultures (four species) in the Greater Panna Landscape (GPL), central India. We performed Random Forest (RF), Generalized Linear Model (GLM) and Boosted Regression Tree (BRT) algorithms. The AUC values for the predictive distribution of nests were 0.97, 0.90, 0.97 for RF, GLM and BRT, respectively, while for roost distribution it was found to be 0.76, 0.63, 0.74 for RF, GLM and BRT, respectively. We ensembled the predictions of all three methods for better accuracy and combined the model outputs. We then performed zonation analysis on the final map and used Human footprint as a proxy for conservation cost to define spatial prioritization for conservation inputs. The results reveal that the GPL has a total of 9,402 sq. km. area within the top 20 ranks in terms of conservation prioritization for nesting and roosting. Given the cost value, the top 20 ranked units will account for approximately 60% of the critical habitats and these may be the focus of long-term conservation inputs to sustain the vulture populations in the landscape. The spatially explicit outputs based on the robust methodology involving intensive fieldwork and ensembled modelling offer a basis for local scale and landscape scale actions, which can be replicated in other parts of the vulture distribution ranges.

Key words: Ensembled model, Conservation priority, Central India, Cliff-nesting, Roosting

Introduction

Vultures play an important role in the ecosystem through scavenging (Campbell 2015, Jha et. al. 2020) but currently, these avian obligate scavengers, are the most threatened functional guild in the world (Şekercioğlu et al. 2004). A study done in Kenya, shows that the number of the mammals and the time spent by them at the carcass, along with the decomposition rate of carcasses to increase 3-fold, in the absence of vultures (Ogada et al. 2012). Buechley and Şekercioğlu (2016) have argued that the decline in the vulture population may contribute to increase in the facultative scavenger population, and trophic cascade through increase in predation, competition and invasion. It has been further reviewed that this increase in the time of contact, and the number of mammalian species at the carcass, increases the risk of spread of zoonotic diseases among humans, livestock and other wildlife (Heever et al. 2021). Another study shows, that replacing the natural process of carcass removal by vultures may raise the emission of greenhouse gases resulting in additional incurring of environmental, as well as, economic costs (Morales-Reyes et al. 2015).

In the Indian context, the country harbors nine species of vultures, seven of which are found in the central part of India viz. the state of Madhya Pradesh (Jha et. al. 2020). The central India is also considered currently as a 'stronghold' for vultures (Jha et al., 2020). However, since the beginning of the century, the Indian subcontinent has experienced a sharp decline in the population of the *Gyps* vultures, especially the Indian Vulture (*Gyps* *indicus*) and the White-rumped Vulture (*Gyps bengalensis*) due to the unchecked usage of the veterinary drug 'diclofenac' as established by researchers (Green *et. al.* ,2004). Markandya et al. (2008) have studied and found a significant association between the decline of vulture population in India and the human health impact from rabies. Jalihal et al. (2022) have also argued that in India, vultures have a role to play as biological agents for waste management and public health maintenance. A study on the conservation priority areas of the old-world vultures has found that the south Asian region holds a huge share in the top 30% of the conservation priority areas for the old-world vultures (Santageli et al. 2019). Therefore, an understanding of the relationship between the influencing variables and distribution of vultures is crucial for the conservation and effective management of the forest areas important for these raptors (Di Vittorio et. al. 2012, Guerrero-Casado et. al. 2013). Such scientific information can help identify and address the local problems in a more specific manner.

Modelling of species distribution is one of the efficient tools to meet this need (Rushton et al. 2004). Application of the statistical techniques on the data derived by geographic information system (GIS) resulting in a predictive habitat modelling is essential for this purpose (Guerrero-Casado et. al. 2013). More importantly, when the conservation of a species is of concern, performing statistical analysis and presenting the results to the academic community alone may be insufficient. Rather the scientific information should be translated into practical solutions in the field, which can guide and support in decision-making for the conservation planners, policy makers and forest managers. In this regard, tools such as spatial prioritization maps obtained from distribution modelling are useful and much needed for conservation planning (Lehtomäki and Moilanen, 2013). Species distribution modelling (SDM) work as an efficient tool to the forest managers for resource allocation in a more productive way, for the conservation of species (Fois et al., 2018; Pecchi et al., 2019). Our study investigates the essential components needed for vulture conservation in the Greater Panna landscape (GPL) through an ensemble of different predictive distribution modelling methods. Parts of the GPL have been shown to fall under the ‘high’ and ‘moderate’ vulture habitat suitability categories (Jha and Jha, 2021). We produce spatially prioritized maps for this landscape to aid in the conservation efforts of this fragile species. Existing data show that vultures are among the most extinction-prone birds in the world, and are in need of urgent attention for conservation and investment (Buechley et al., 2019) However, to address the conservation problems around vultures more efficiently, we emphasize that there is no “one-size-fits-all” approach. Rather, approaches must look at the species distribution and its deciding variables at a more local scale, and address the conservation issues accordingly.

Study Area

The study area (Figure 1) is known to be GPL and extended between 81.89047389°E to 78.28682278°E longitude and 24.88715889°N to 24.23466306°N latitude with an area of 47,621 sq. km.

The area experiences four seasons in a year – winter from January to February, summer in the months of March, April and May, the southwest monsoon from June to September, and lastly by the post monsoon season during the months of October to December. The GPL is experienced to be a hot and semi-arid place with less humidity.

The river Ken is the main perennial river in the region, which is the sub-basin of the Yamuna- a main tributary of the Ganges. Shyamri, Bearma and Sonar are the main tributaries of the Ken River. The forest type found here is Tropical dry deciduous. The soil type in the study area shows the spectrum of shallow to deep black soil. The alluvial soil is found along the river courses, while the northern Vindhya scarplands have yellowish sandy soil due to the weathering of granite rocks.

The study area is spread over 11 districts – 8 in the state of Madhya Pradesh and 3 in the state of Uttar Pradesh, which are part of the Sagar Damoh Plateau, Vindhyan scarplands, and the Kaimoor hills. The unique geographical features; i.e., gorges and river escarpments provide suitable habitat for cliff-nesting vultures.

The GPL holds one tiger reserve and four wildlife sanctuaries as Protected Area (PA). These include Panna Tiger Reserve (PTR), Nauradehi Wildlife Sanctuary (NWLS), Veerangana Durgawati Wildlife Sanctuary (VDWLS), Ken Ghariyal Sanctuary (KGS), Ranipur Wildlife Sanctuary (RWLS). Apart from these, the landscape also holds 12 other forest divisions in parts or full, which do not come under the PA category.

The gorges, river escarpments, and cliffs with steep slopes and ledges provide shelter to the vultures for roosting as well as for nesting. Additionally, the rocky surfaces which are free of vegetation, facilitate the development of thermals or hot air columns which aid the vultures in soaring. Since the entire landscape is full of cliffs and gorges, the vultures also experience the orographic lift which greatly helps them in their passive flight. The communities in the GPL are majorly engaged in agriculture and livestock farming. The large livestock population yields adequate carcasses resulting in potential food sources for the vultures.

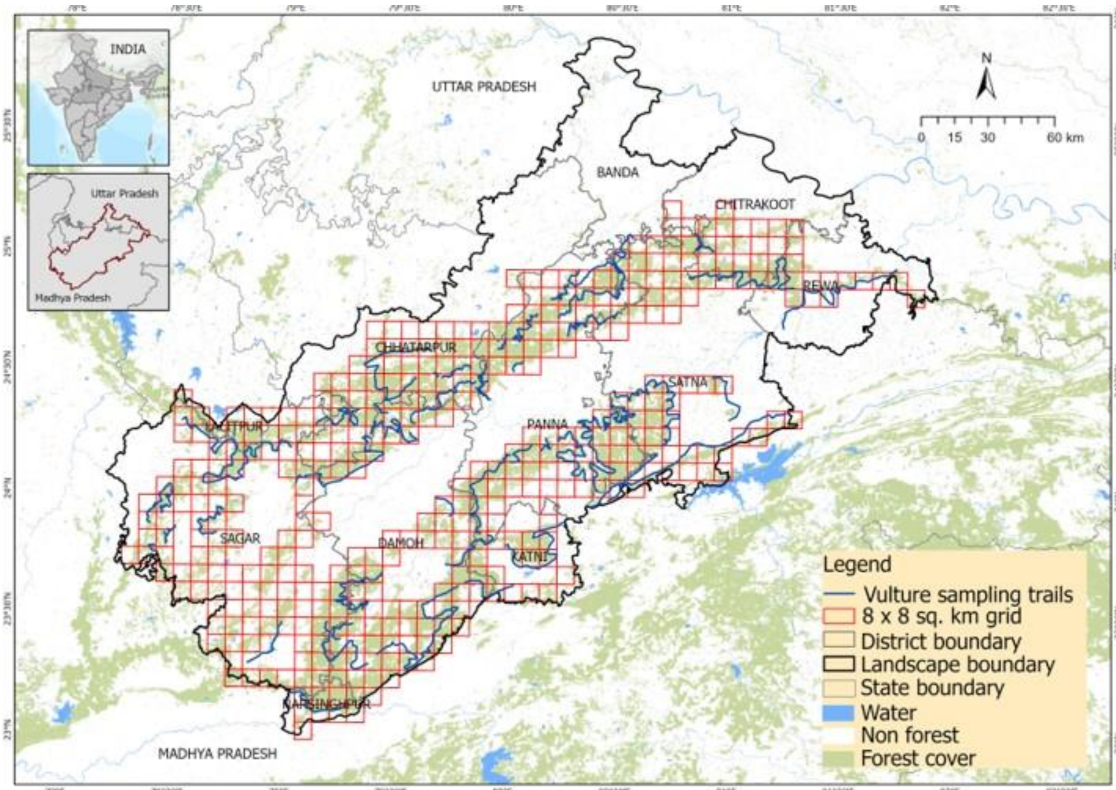


Figure 1 The trails covered in Greater Panna Landscape (GPL) for 'Area Search'

Method

Data collection: The entire study area was divided into nested grids of 8x8km and 2x2km (Figure 1). During the visit to the sampling area, “Area search” (Ralph, Geupel, Pyle, Martin, & DeSante 1993; Dieni & Jones 2002) methodology was followed to observe the cliff-nests and the roosting sites of the vultures. A total of 2232.27 km of trail was covered for the survey. The survey was conducted from half an hour after sunrise, up to 10:30-11:00 am., in order to be sure about the occupancy of the vultures at the nests and the roosting sites. A sufficient distance was maintained at all times during the observation to avoid disturbance to the vultures. Spotting scopes and binoculars were used to overcome the distance.

Statistical analysis: A distribution modelling was done for the cliff-nest sites as well as the roosting sites, separately, using the 'sdm' package (Naimi and Araújo, 2016) in R Studio ver.1.2.5019. For deriving the environmental variables ArcGIS Pro ver. 2.2.0 was used. 12 raster layers were prepared as predicting environmental variables (Table 1) of uniform projection, extent, and 100m resolution, keeping in mind the abrupt change in terrain and geomorphology of the landscape. Multi-collinearity was detected using the variable inflation factor (VIF) index, for the variable layers using 'vifcor' function in R. It was found that no multi-collinearity existed among the variable layers (Table 1).

Sl. No.	Environmental variable	Raster layers	Abbreviation	Source	VIF
01	Topographical elevation	Digital elevation model (DEM)	DEM	ASTER	1.63
02	Topographical slope	Slope raster layer derived from DEM	SLP	Derived from DEM	2.81
03	Direction of slope used for nest	Aspect raster layer derived from DEM	ASP	Derived from DEM	1.01
04	Vegetation cover	Normalized Difference of Vegetation Index (NDVI)	NDV	LANDSAT (2018)	1.25
05	Local temperature	Land Surface Temperature (LST)	LST	LANDSAT (2018)	1.02
06	Availability of stream water	Stream density	SRD	Derived from DEM	1.12
07	Disturbance from linear structures	Distance from Road and rail network	RDI	DIVA-GIS	1.22

08	Disturbance from the powerline structures	Distance from high power transmission lines	PDI	Digitized from Google Earth Image	1.13
09	Other anthropogenic disturbance	Nightlight data	NTL	DMSP (2018)	1.05
10	Measure of ruggedness	Standard deviation of DEM	RUG	Derived from DEM	2.84
11	Proximity from the known food sources	Distance from the 'gaushala' (Cow shelters)	GDI	Field data	1.23
12	Availability of wind power for taking flight	Wind Power density	WPD	www.vortexfdc.com	1.50

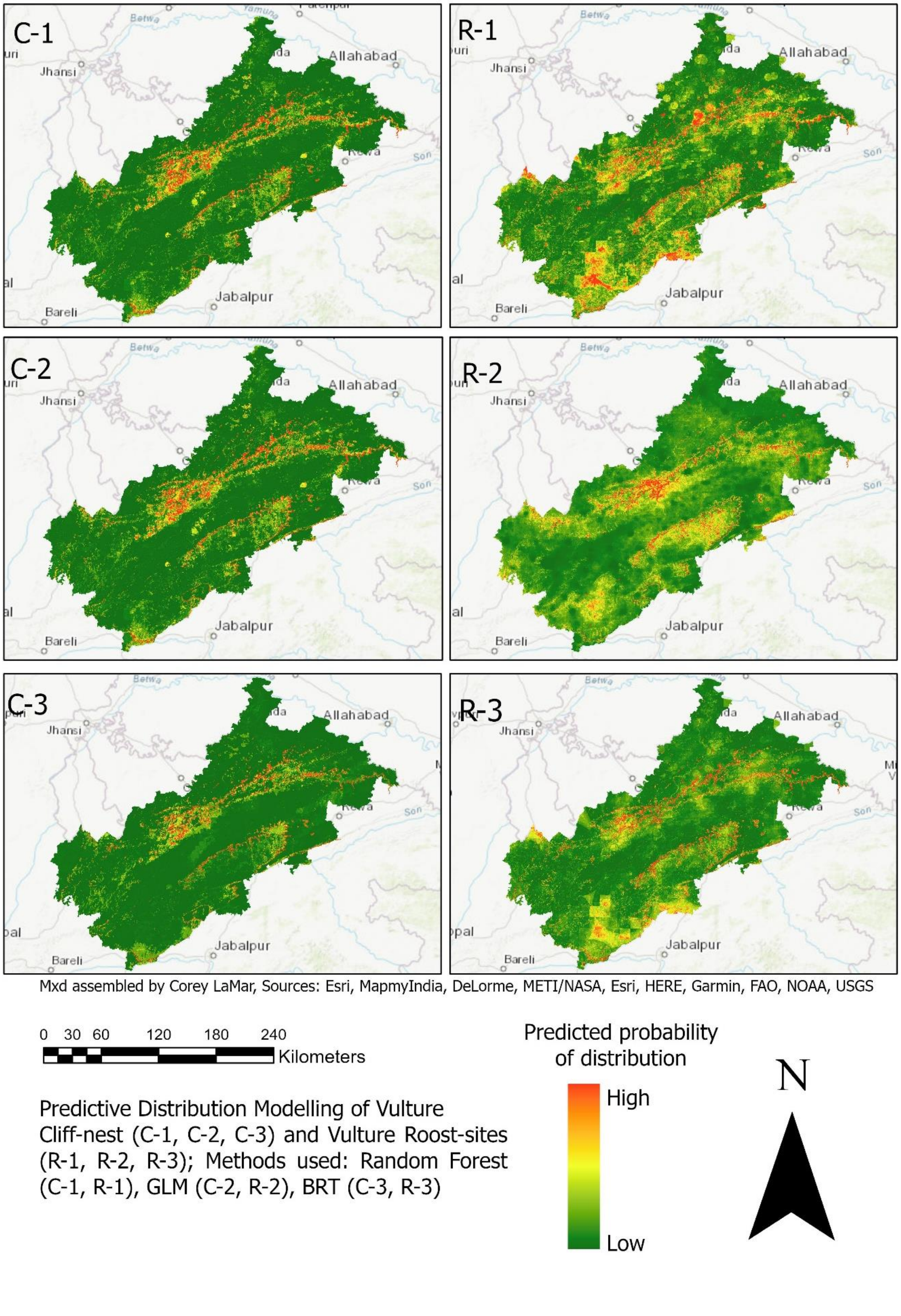
Table 1 – Variables and their respective raster layers, with their abbreviation, used for modelling along with their VIF scores

All the raster layers were stacked together. Initially, we have deployed three modelling methods, Random Forests (RF) (Breiman, 2001), Generalized Linear Modelling (GLM) (McCullagh & Nelder, 1989), and Boosted Regression Trees (BRT) (Friedman, 2001) individually, following which all the three predicted models were ensembled. Studies have shown that ensembled modelling gives better accuracy for species distribution (Grenouillet et al., 2011). We generated random background points according to Barbet-Massin et al. (2012) with the help of 'sdm' package. For evaluating the model, sub-sampling method was implemented which is part of the 'sdm' package (Naimi and Araújo, 2016). The original data was split into two parts, 70% for taring and 30% for testing purpose. After performing all the statistical analysis to predict the distribution of the species of interest, it is of much relevance to also determine the importance of predictive variables, from the point of view of both practicality and management. The ‘sdm’ package determines the ‘variable importance’ and the ‘response curve’ in order to show the predicted effect of the variable on the species. In order to get the ‘response curve’ of the variables the method by Elith et al. (2005) was applied here through the ‘sdm’ package. The ‘variable importance’ has been determined by considering the ‘1-correlation’ as described by Thuiller et al. (2009) which has been incorporated by Naimi and Araújo (2016) in their ‘sdm’ package.

The spatial layers produced by the predictive distribution modelling were further used by the Zonation software (Zonation GUI 4.0.0rc1_compact) along with the spatial layer of Human Footprint Index as a proxy of cost of conservation, as used by Santageli et al. (2019). This was done for deriving priority areas for the nesting and roosting of the cliff-dwelling vultures. The distribution probability value of nesting and roosting has been considered as the ‘conservation feature’. For capturing the ‘conservation feature’, i.e., the predicted distribution probability of the vultures for each cell, we merged the two layers of cliff-nest and roost site that have been modelled for predictive distribution. Furthermore, we downscaled the resolution to 1 KM to match with the spatial layer of Human Footprint Index. Core-area Zonation (CAZ) method (Santageli et al. 2019) was used for the ranking of the of the priority areas. The CAZ essentially interprets that the areas with high priority or top ranking will have the highest cumulative value for the distribution of cliff-nest and roost sites, and low human footprint and low cost for conservation.

Results

Predictive distribution for cliff-nest and roosting site: A total of 30 cliff-nest sites and 31 roosting site locations were recorded between November, 2018 and May, 2019. It was found that the species assemblage in the nesting and the roosting sites were not same. The cliff-nests found during the study were only of Indian Vulture and Egyptian Vulture, whereas in the roost sites, these two species were accompanied by the Red-headed Vulture, Himalayan Griffon, and the Eurasian Griffon. The White-rumped Vulture was sometimes found accompanying the two species, but very rarely by the Cinereous Vulture. In these models no species were considered separately. Presence of the nest of any species of vulture had the same significance in this study, except for the nest of the White-rumped Vulture and the Red-headed Vulture. Because these two species were mostly found to build nests on trees. Based on the above-mentioned methodology, 1000 background points were generated randomly and RF, GLM, and BRT were performed with 10 replications for cliff-nesting and roosting distributions, separately (Figure 2). The model's mean performance was calculated. For the goodness-of-fit metric the deviance was calculated. For cliff-nest distribution deviances were found to be 0.13, 0.2, and 0.15 for RF, GLM, and BRT methods, respectively. Similarly, the deviance for roost-site distribution was estimated to be 0.24, 0.27, and 0.24 for RF, GLM, and BRT respectively. Threshold independent statistics, i.e., area under the curve (AUC), which was calculated for predictive distribution of cliff-nest was found to be 0.97, 0.90, and 0.97 respectively for RF, GLM, and BRT (Supporting information). The AUC values for the prediction of roost-site distributions were 0.76, 0.63 and 0.74 respectively, for RF, GLM and BRT (Supporting information). The three predictive distributions for both cliff-nest and roost sites were ensembled for better accuracy (Figure 3).



Predictive Distribution Modelling of Vulture Cliff-nest (C-1, C-2, C-3) and Vulture Roost-sites (R-1, R-2, R-3); Methods used: Random Forest (C-1, R-1), GLM (C-2, R-2), BRT (C-3, R-3)

Figure 2 Modelled distribution of cliff-nest sites (left) & roost sites (right) for different modelling methods

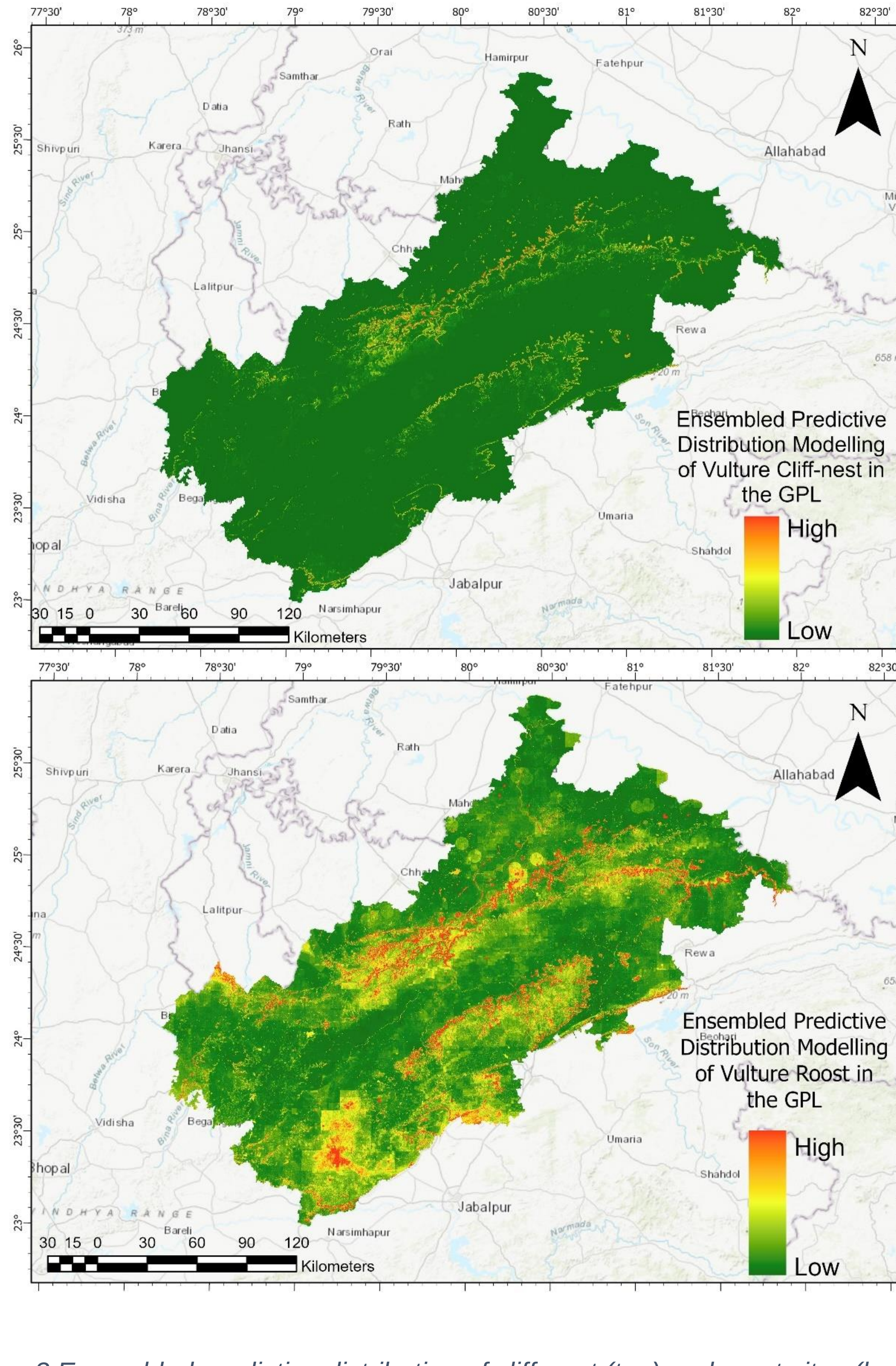


Figure 3 Ensembled predictive distribution of cliff-nest (top) and roost sites (bottom) of vultures in GPL

We also found that for the overall predictive distribution of the cliff-nest (averaging all the models), based on the correlation metric, the major variable importance is shown by two variables namely ruggedness (49.8%) and slope (11.2%). However, based on the AUC metric, only ruggedness had major importance, i.e., 17.5%. The rest of the variables show very low level of importance based on both the metrics. We also found other variables to show major importance, when the individual modelling methods were considered (Table 2).

We further estimated the importance of variables for the prediction of roost site distribution, based on correlation metric and averaging values of all modelling methods. Slope (20.7%), ruggedness (19.4%) and wind-power density (12.7%) were found to be majorly contributing factors. But, when the AUC metric is considered, almost all the variables showed low level of importance, with ruggedness (9.4%) being the most important (Table 2).

From the response curves of the environmental variables, we found that the predictive distribution of both the cliff-nests and roost sites increases, with the increase in ruggedness and the slope of the terrain. The roost site distribution also shows a negative relation with the wind-power density.

	Modelling method	Metric	ASP	DEM	GDI	LST	NDV	NTL	PDI	RDI	RUG	SLP	SRD	WPD
Cliff-nest	RF	Correlation	4.4	3.6	8.9	2.6	11.9	1.1	2.8	10.5	15.7	17.7	4.2	10.3
		AUC	0.3	6.1	2.8	1.1	2.9	0.7	2.6	9.7	9.9	4.1	3.1	4.7
	GLM	Correlation	1.7	10.2	1.4	2.8	0.9	10.7	8.9	5.1	21.9	19.3	0.9	23
		AUC	0.6	9.3	0.3	1.6	0.5	6.7	7	1.9	7.3	9.7	0.8	2.4
	BRT	Correlation	1.9	1.6	4.5	0.9	5.8	0.4	1.6	6.2	20.5	25.2	3.2	4.7
		AUC	0.3	5.2	3.1	0.2	1.5	0.6	5.6	6.4	11	4.2	2.9	3.1
	Overall	Correlation	1.7	1	1.8	0.7	1.4	6.2	2.2	3.4	49.8	11.2	0.9	4.8
		AUC	1.1	1.5	2.2	0.3	0.3	4.8	0.9	2.2	17.5	2.6	0.2	2.3
Roost-site	RF	Correlation	4.4	3.6	8.9	2.6	11.9	1.1	2.8	10.5	15.7	17.7	4.2	10.3
		AUC	0.3	6.1	2.8	1.1	2.9	0.7	2.6	9.7	9.9	4.1	3.1	4.7
	GLM	Correlation	1.7	10.2	1.4	2.8	0.9	10.7	8.9	5.1	21.9	19.3	0.9	23
		AUC	0.6	9.3	0.3	1.6	0.5	6.7	7	1.9	7.3	9.7	0.8	2.4
	BRT	Correlation	1.9	1.6	4.5	0.9	5.8	0.4	1.6	6.2	20.5	25.2	3.2	4.7
		AUC	0.3	5.2	3.1	0.2	1.5	0.6	5.6	6.4	11	4.2	2.9	3.1
	Overall	Correlation	2.7	5.1	4.9	2.1	6.2	4.1	4.5	7.3	19.4	20.7	2.7	12.7
		AUC	0.4	6.9	2.1	1	1.7	2.6	5.1	6	9.4	6	2.3	3.4

Figure 2 Variable Importance values based on correlation metric and AUC metric for all modelling methods

Spatial Prioritization: Figure 4 gives the spatially prioritized areas in a rank wise manner for the conservation of the vultures. The top ranked priority areas of conservation have a higher value of distribution probability of vultures and lower human footprint index. Therefore, the top ranked areas will have lesser cost for conservation while securing higher amount of potential cliff and roost areas for the vultures, when compared to other areas. According to the result, top 20% ranked land area of the GPL amounts to 9,402 sq. km., but the total area of PAs inside the landscape is only 2,134 sq. km. Therefore, only one fourth part of the top 20% important vulture areas come under the PA category. Interestingly, from the graph below (Figure 4) it can be found that only by conserving the 20% of the top prioritized area in the GPL, more than 60% of the vulture distribution can be saved, including the cliff-nesting and the roosting sites. From the perspective of conservation costs, (Figure 4) if the total cost of conservation of the entire vulture distribution of the GPL is considered as 1 unit, it takes less than 0.2 unit of cost to conserve approximately 60% of the distribution of vultures in the GPL. Moreover, one fourth of that 60%, i.e. 15% distribution of vultures, is already protected under the PA category.

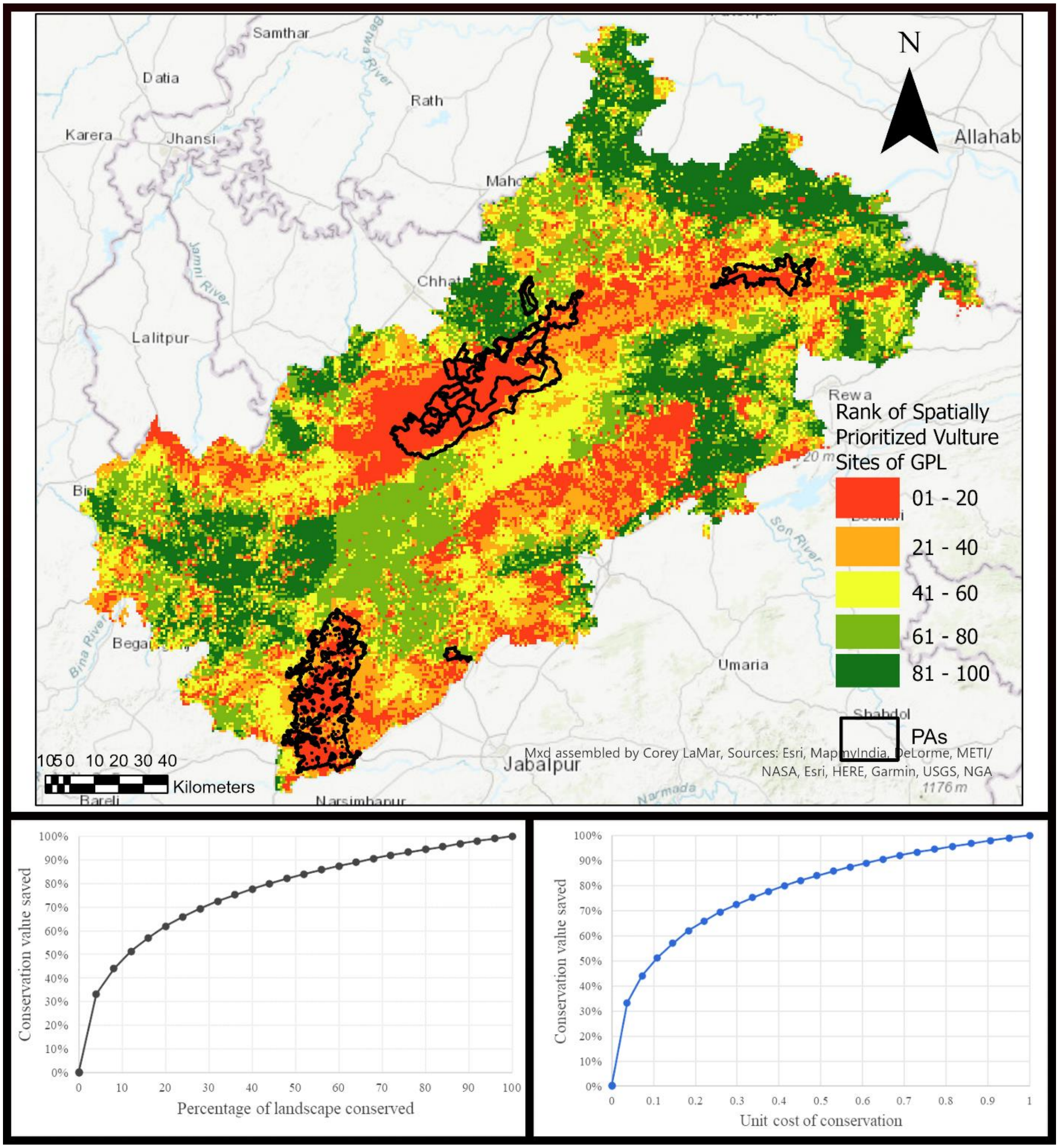


Figure 4 Spatially Prioritized zones for vultures in the GPL (top). Proportion of conservation value saved w.r.t. landscape conserved (bottom-left). Conservation value w.r.t cost (bottom-right)

Discussion

Distribution of cliff-nest: The major influencing factors for the distribution of the cliff-nest are ruggedness (RUG) and slope (SLP). The remaining variables have shown to have much less influence. The distribution probability is positively related to the ruggedness and slope. Ruggedness is a measure of the variability in the height of the terrain. A larger variation in height actually defines a larger difference in the upper and lower limit of any cliff or river escarpment. The terrains with larger ruggedness values are thus less likely to be accessed by predators. Also, such areas experience slope wind which is efficiently used by vulture species during taking flight. Such terrain characteristics also restrict major human activities. Less human disturbances further reinforce the reason to build nests in rugged terrains, with steep slopes. The GPL is known for such rugged terrain as a result of cliffs with steep slopes and rocky river escarpments. The cliff-nesting vultures have often been found to build their nests on the ledges of these cliffs and river escarpments. This ensures better protection of the nests from predators and reduced anthropogenic disturbances. Many studies have also shown that building nests at higher elevations with steep slope, have been found to be a major deciding factor, for vultures (Poirazidis et al., 2004; Dobrev and Popgeorgiev, 2021). Supporting our results, such an increase in the probability of occupying cliffs for nesting, with increasing ruggedness of terrain have been reported for Bearded vultures in Spain (Donazar et al., 1993), African White-backed Vultures in Swaziland (Bamford et al., 2009), and for Eurasian Griffon vultures in the Iberian Peninsula (García-Ripollés et al., 2005).

Distribution of roost-site: When both the correlation and AUC metrics are considered, the ensembled model shows that for the distribution of the roost-sites the major influencing factors are slope, ruggedness, and wind-power density. Among these predictors, wind-power density is a negatively influencing factor, while the rest are positively related to the distribution of roosting sites. It is thought that reduction in the cost of thermoregulation, reduced predation risk, and increase in the efficiency of foraging are the reasons for roosting (Eiserer, 1984; Ydenberg and Prins, 1984; Yamac, 2006). Therefore, we can assume that high wind-power density may cause a higher cost of thermoregulation in winter nights. For ease of thermoregulation, vultures avoid roosting in areas with high wind, thus showing a negative relation with this variable. Often, the roosting sites in the central Indian landscape are found near carcass dumping areas which are generally situated in agricultural areas and human dominated regions. These areas are often less rugged with lower slopes compared to nesting areas. Thus, this may have actually resulted in the lower variable importance for ruggedness and slope, as shown in our results. Earlier studies on the roost selection of the Egyptian Vulture in northern Spain and roost selection of Black Vulture in Central Amazon have also shown vultures to set their roosts near foraging areas (Donazar et al. 1996; Novaes and Cintra 2013)

This predictive distribution of roosting sites of vultures indicates that, there may be a difference in their habitat preferences based on the local environmental factors. This also indicates that the creation of the carcass dumping sites, along with the establishment of new cow shelters in the future, may actually have profound effects on the roosting behavior of the vultures in the landscape. However, we recommend further scientific studies should be conducted to better understand these effects.

Conservation Priority Areas: A significant amount of high priority area for vultures is lying outside the PAs (PTR, NWLS, VDWLS, RWLS, KGS) in GPL which is in agreement with the study by Santageli et al. (2019), and Buechley et al. (2021) for other the old-world vulture species. The unprotected forest areas in the GPL also harbour significant vulture populations. Due to its rocky and rugged terrain with steep slopes and deep river escarpments, vultures often find suitable nesting or roosting sites across the GPL, irrespective of the protection status of the area. The presence and functioning of 'gaushalas' or cow shelters are also likely to shape the distribution of the vultures in the landscape. Generally, the establishment of a gaushala is accompanied by the creation of a dumping site nearby to facilitate the dumping of cattle carcasses from the shelter. With the normalization of such mismanaged practices, the gaushalas with larger capacities end up having a bigger contribution to the dumping. It has been found that vultures roost in large numbers by the dumping sites due to the availability of carcasses. In the GPL, the Pawai region in the district of Panna and the Baghdari Fall region in the district of Damoh are two prominent places with large dumping sites. Both of these places, which are located outside PAs have been found to be used extensively by the vultures as roosting sites. During the survey, it has also been found that the practice of dumping cattle carcasses is prevalent around the fringes of the villages, which in most cases are by the forests or rivers. Dumping sites act as a regular food source for the vultures along with other mammalian scavengers, especially domestic dogs. All of these dumping areas, mostly being situated outside the PAs, go unsupervised and pose potential threats to the well-being of the vultures. Such unregulated dumping sites are a potential source of carcasses that have been contaminated with 'diclofenac' or other veterinary drugs which are harmful to vultures, as well as, the other animals feeding on it. In order to support a steadily available source of food to the vultures, it is highly recommended to develop a supervised mechanism through which only tested and uncontaminated carcasses would be dumped at such dumping sites. Since only 15% of the vulture distribution areas are under protection through PA categorization, further protection can be ensured through developing conservation reserves or community reserves outside the PAs. Earlier studies have shown that assigning new protected areas are likely to facilitate the increase in the vulture population (Gavashelishvili et al., 2006). Moreover, the current perceptions of the cost of vulture conservation are parochial and most often does not account for the larger ecosystem and public health benefits provided by these scavengers. With India already being over-burdened by infectious diseases, policy makers should be constantly reminded that the decline in the population of the vultures due to lack of conservation, may incur us a huge cost in the public and animal health sectors, (Markandya et al. 2008) and risking the decade-long conservation efforts of other wild charismatic species in the country.

Conclusion

There are only few studies done in the central Indian landscape which have predicted distribution of vultures, incorporated local factors and also treated nesting and roosting sites separately. Since nesting and roosting sites serve different purposes for the birds, it is very essential to treat them independently while performing predictive modelling. Our study shows that rugged terrain with steep slope are the main influencing factors for the distribution of the cliff-nests as well as roost sites in the landscape. Roosting is often done in terrains with lesser ruggedness and slope due to the need for setting it near the foraging areas, which are mostly the dumping sites in human dominated parts of the landscape. Therefore, as a conservation measure it is mandatory to avoid developmental projects which involves the alteration or disturbance of these highly suitable and prioritized areas for nesting and roosting. This is a major concern because this study shows that a large amount of suitable area remains outside the periphery of the Pas like PTR and NWLS, which are of high conservation priority. Since these areas harbor significant vulture populations in the landscape, there is urgent need for their protection status to be upgraded. Our analysis of spatial conservation prioritization shows that the conservation cost of those suitable areas outside the PAs is also comparatively very low which should be encouraging for managers as well as policy makers. Perceiving the relevance and the urgency of the situation, the results of this study has been used for the development of a management plan for GPL (WII, 2022). In addition to the ban on diclofenac, safeguarding critical habitats of these raptors that fall outside PAs is a crucial step that needs to be urgently considered by conservation managers, in order to support the increasing vulture population in central India.

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