

Notable Changes in Conservation Status of Vultures in Uttar Pradesh, India: A Study Based on Occupancy and Habitat Modelling

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Abstract Vultures are key to the functioning of ecosystems but they are assessed to be threatened globally and their numbers are at-risk due to changes in habitat and other factors. This study focuses on identifying localized conservation status changes in vultures over a decade (2011–2020) by assessing habitat occupancy and population in Uttar Pradesh using PRESENCE, GeoCAT and MaxEnt tools. The overall vulture population increased with differing growth rates across species (11–18%). The Extent of occupancy of Egyptian, Red-headed, and Indian vultures, and Himalayan Griffon increased over the decade but White-rumped and Cinereous vultures showed decrease in this parameter. The occupancy (ψ) and suitable area for Indian, White-rumped and Cinereous vultures decreased while, Egyptian and Red-headed vultures showed gains. Himalayan Griffon showed increased occupancy but decreased suitable area. On the other hand, Area of occupancy components showed improvement in conservation category in the case of Egyptian Vulture and Eurasian Griffon, but deterioration in Slender-billed Vulture. Remaining vultures (Cinereous, Himalayan Griffon, Indian, Red-headed and White-rumped) with continued threatened status were still a cause of concern. Overall, an increasing population coupled with decreasing suitable area indicated the concentration of individuals in

smaller areas leading to enhanced extinction risks. This indicated that the imperiled resident *Gyps* (*G. bengalensis*, *G. indicus* and *G. tenuirostris*) were not recovering post-diclofenac-ban. However, an influx of population without nesting pressure in the wintering habitat indicated a positive future for migratory species. Therefore, management interventions for safeguarding the future of these vulnerable raptors should be concentrated in potentially suitable areas too as predicted in this study.

Keywords AOO · EOO · GeoCAT · MaxEnt · PRESENCE

Introduction

The earth is estimated to be losing thousands of species each year (Pennisi 2022) and the species most likely to disappear are those that serve unique, possibly irreplaceable, functions in their ecosystems. Among others, vultures with distinctive physical traits, are likely to be the first to go extinct (Pennisi 2022). Vultures are an important component in the ecosystem which provide crucial services as the ecosystem's clean-up crew. This includes keeping diseases of humans, wildlife and livestock in check. Ethically also, the intrinsic value of vultures is worth conserving regardless of their environmental value (Brennan and Norva 2021). Unfortunately, ample evidence of global scale declines in vulture populations, especially in the Indian subcontinent, has been recorded (IUCN 2019). This has further highlighted the need for more extensive and rigorous monitoring programs to document species occurrence and detect population changes (Bailey et al. 2004). Therefore, for successful conservation management, accurate monitoring of species and populations is a prerequisite (Brubaker et al. 2013).

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Pennisi (2022) further stated that the “most imperiled” regions include the Himalayan foothills which comprise the *Tarai* and *Bhabar* zones (Mehta and Adyalkar 1962). The northern part of the study area, Uttar Pradesh (UP), a 560 km stretch beyond the Gangetic plains, along the Nepal border, is a major part of the *Tarai* foothills. A good population of resident and wintering vultures are found (Jha 2015; UPFD and BNHS 2021) in this region. Uttar Pradesh is home to eight different species of vultures namely, Cinereous Vulture (*Aegypius monachus* Linnaeus 1766, CV), Egyptian Vulture (*Neophron percnopterus* Linnaeus 1758, EV), Eurasian Griffon (*Gyps fulvus* Hablizl 1783, EG), Himalayan Griffon (*Gyps himalayensis* Hume 1869, HG), Indian Vulture (*Gyps indicus* Scopoli 1786, IV), Red-headed Vulture (*Sarcogyps calvus* Scopoli 1786, RHV), Slender-billed Vulture (*Gyps tenuirostris* Gray 1844, SBV) and White-rumped Vulture (*Gyps bengalensis* Gmelin 1788, WRV). Globally, these species have different conservation statuses and population trends as assessed by the International Union for Conservation of Nature and Natural Resources (Birdlife International 2021a, b, c, d, e, f, g, h).

The current national status of conservation for these species is of major concern since some are under strong decline (EV, IV, RHV, WRV), some face moderate decline (CV), while a couple fall in the uncertain category (EG, HG) and for one the data is insufficient (SBV) (SOIB 2020). The past decades have been eventful for vultures in the Indian subcontinent, including UP. While Prakash et al. (2007) noted a sharp dip in vulture numbers, the reason for this was also subsequently detected (Oaks et al. 2004) during the first decade (2000–2010) of the century. However, further studies (Prakash et al. 2012; 2017) suggested the next decade (2010–2020) was the decade of recovery for these imperiled vultures in India and other countries of the subcontinent. Within India, at the regional level, there have been contrasting trends of rise and fall in vulture population reported from different states over the last decade (Chhangani 2009; Kamboj 2016; 2018; Jha 2015; 2017; MPFD 2019; 2021; UPFD and BNHS 2021). Therefore, comparative temporal studies may provide definitive trend to assess the effectiveness of conservation strategies.

Studies of biodiversity dynamics have been cast on either long (systematics) or short (ecology) time scales of decades to centuries (Machado-Stredel et al. 2022). Quite a few researchers (Chong et al. 2012; Baidya et al. 2016; Banville et al. 2017) noted that decadal dynamics could be good enough for studying some ecological parameters of birds. In order to get a more lucid picture of vulture population and habitat dynamics, different ecological modelling tools could be employed. The IUCN Red List relies on geographical range estimates for assessment of species extinction risk through Extent of occurrence (EOO) and Area of occupancy (AOO) (Gaston 2009; Kass et al. 2021). Extent

of occurrence is the “spatial spread of the areas currently occupied by the taxon” and is not intended as an estimate of occupied areas but as an indication of the spread of extinction risks to the taxon (IUCN 2019). Area of occupancy represents the “area of suitable habitat currently occupied by the taxon” within the EOO at a defined reference scale of 2 km × 2 km (IUCN 2019).

Both EOO and AOO are assessed using Geospatial Conservation Assessment Tool (GeoCAT) (Bachman et al. 2011; Joshi et al. 2017). Another popular method is Species Distribution Modelling (SDM) for ascertaining the potential range of distribution, which complements EOO in producing actual distribution (Kamino et al. 2012). Such a study could provide a means to evaluate the potential opportunities remaining for conservation in this localized vulture region with high richness (Loiselle et al. 2010). Extent of occurrence captures the overall geographic spread of the localities where a species occurs concurrently (Gaston and Fuller 2009) but may not cover the full suitable area of a region since it is the minimum convex polygon of occurrence sites. However, the SDM provides a wider picture of habitat, providing potentially suitable areas (Kamino et al. 2012). A third tool to understand species distribution is occupancy modelling by estimating site occupancy values using PRESENCE and establishing habitat relationships (Amettler et al. 2017; Rehman et al. 2021).

With the above background, this paper is aimed at studying changes in the conservation status of vultures in an imperiled region of northern India, Uttar Pradesh, using selected modelling tools by (i). Assessing change in occupancy over a decade (2010–2020). (ii). Comparing Extent of occurrence and Area of occupancy changes after ten years and (iii). Analyzing temporal change in population status and suitable habitat availability.

Materials and Methods

Study Area

Uttar Pradesh (UP) was chosen as the study area since it possessed a sizeable population of vultures and suitable habitats (Tropical moist and dry deciduous forests, hilly terrain with cliffs and abundant water bodies) for roosting and foraging (Campbell 2015; Jha 2015; Jha and Jha 2021). The study area (240,930 km²) is situated between 23°52'N and 30°24'N latitude and 77°5' and 84°38'E longitude (ISFR 2021). It is divided into four ecozones (Jha 2015): Tarai, Gangetic, Semi-Arid and Vindhyan-Bundelkhand with varying combination of vegetation, temperature, precipitation and topography (Fig. 1 and Table 1). Both Tarai and Gangetic plain have a flat terrain but the former has tropical moist deciduous forests while the latter is devoid of forests

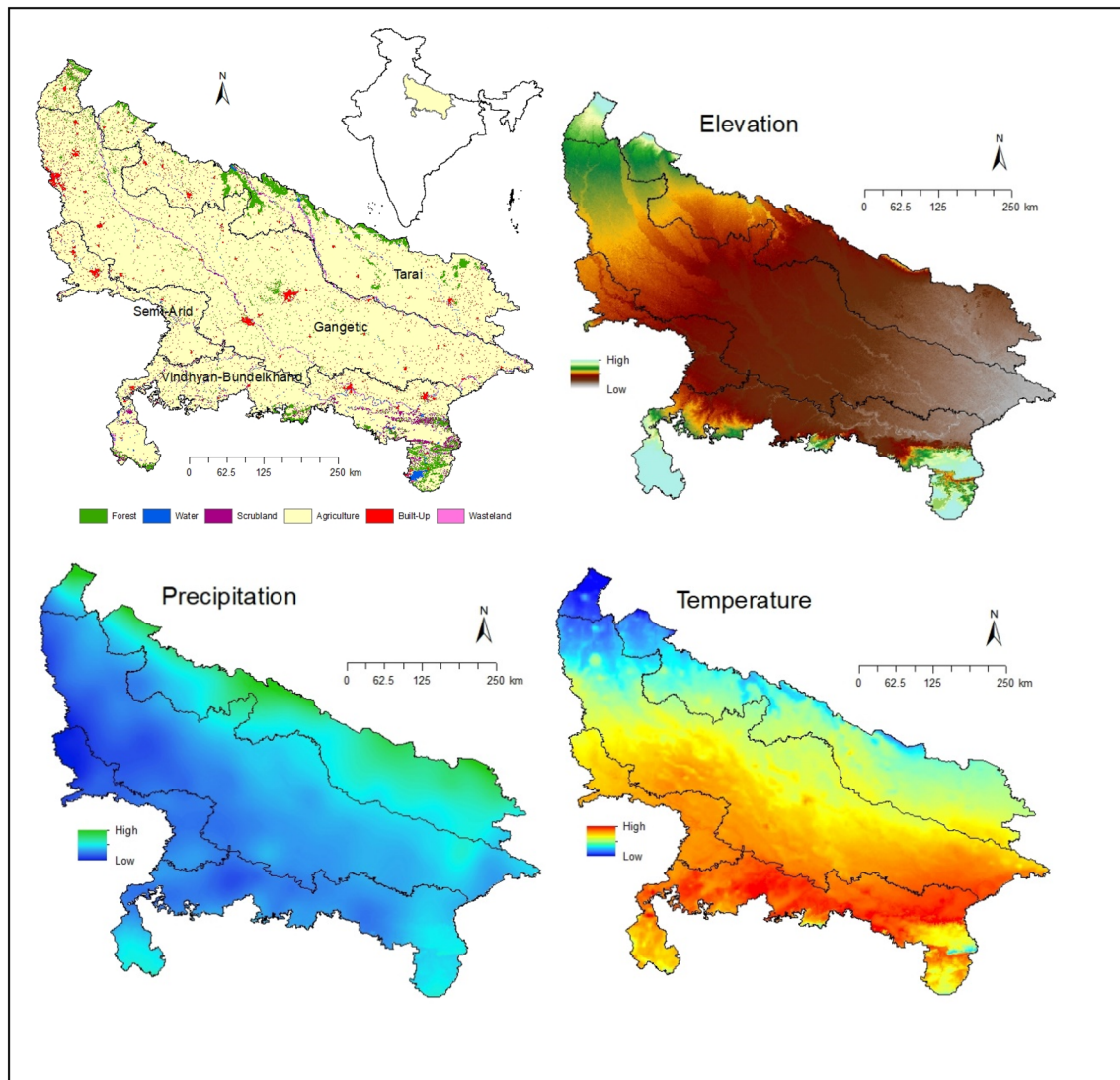


Fig. 1 Location, ecozone delineation, elevation and ombrothermic maps of Uttar Pradesh (Adapted from Jha et al. 2022). Top left has the land use land cover classes in different ecozones (Data source:

Buchhorn et al. 2020) followed by elevation, temperature and precipitation maps in clockwise direction (Data source: USGS EROS 2018; Fick and Hijmans 2017)

Table 1 Ecozone wise temperature, rainfall and elevation ranges of the study area

Ecozones	Temperature*	Rainfall*	Elevation**
Tarai	21.25–25.53 °C	816–2120 mm	44–935 m
Gangetic	23.56–26.27 °C	635–1491 mm	23–277 m
Semi-Arid	25.13–26.11 °C	603–943 mm	58–300 m
Vindhyan-Bundelkhand	24.01–26.56 °C	751–1248 mm	33–644 m

* (Fick and Hijmans 2017), ** (USGS EROS 2018)

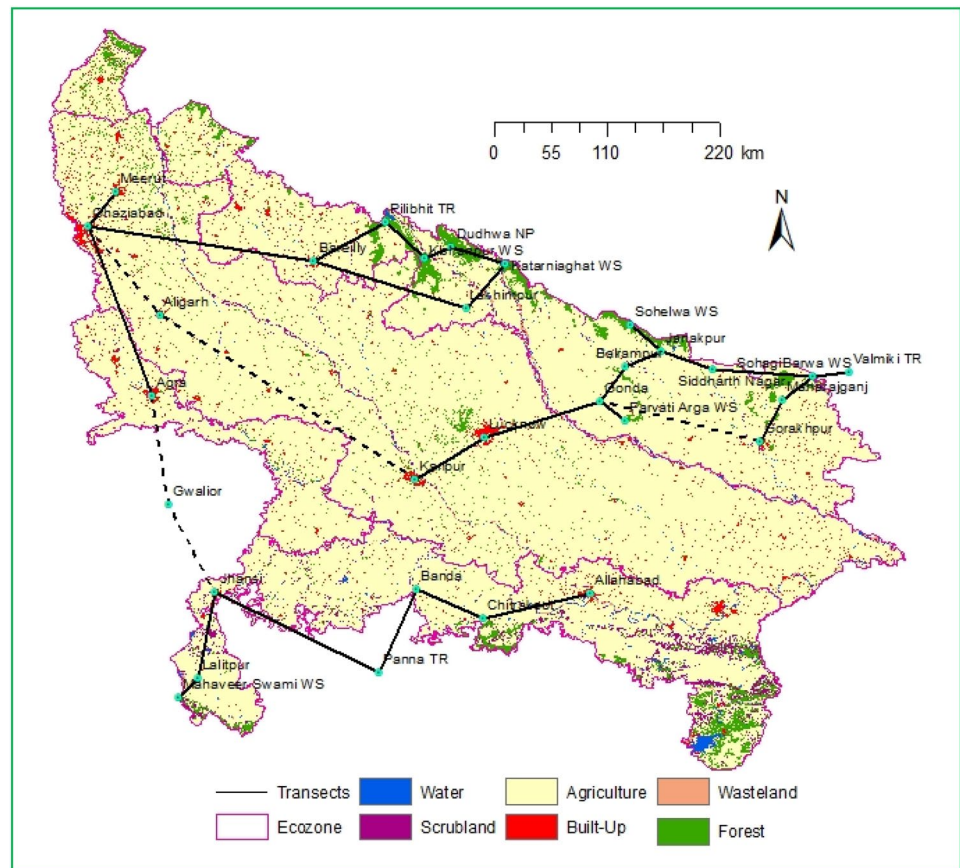
but has scattered trees in agricultural areas. The Semi-Arid ecozone has ravines and tropical thorn forests. The Vindhyan-Bundelkhand ecozone has an undulating terrain

marked by tropical dry deciduous forests. Due to varied ecological features and foraging opportunities there is differing richness and abundance of vultures in these ecozones.

Data Collection

Occurrence data of vultures was collected through multiple transect surveys which were carried out on foot, in motor vehicle and by train (Fig. 2). This primary data of winter 2020–2021 (December to March) was further supplemented by incorporating research grade, citizen science data from eBird (Sullivan et al. 2009) and iNaturalist (iNaturalist users and Ueda 2020) as well as data from published records (Jha 2015; Ansari 2015) for the study area. These combined data sets were used to build species distribution models to study

Fig. 2 Study area showing survey routes and major places covered along the road transects. Dashed lines indicate railway transects (Jha et al. 2022)



habitat suitability. In order to analyse decadal change in occupancy using PRESENCE and GeoCAT, the occurrence data was segregated for 2010–11 (henceforth, 2010 survey) and 2020–21 (henceforth, 2020 survey).

Occupancy Estimation

A fishnet was created (Fig. 3) within the political boundaries of UP (240,930 km²). Each cell was considered to correspond to the occupancy site or foraging area of vultures set at 250 km² (total 1093 cells) while, each sub-cell was considered to correspond to the replicates or shelter area set at 10 km² (25 sub-cells per cell) following Jha et al. (2020). Using the presence locations as reference, each sub-cell was marked as ‘1’ (detected) or ‘0’ (not detected). This data was then fed into PRESENCE 2.13.6 software (Hines 2006).

Standard occupancy model [$\Psi(\cdot), p(\cdot)$] or single season occupancy model was run for each species (MacKenzie et al. 2006; Chibesa and Downs 2017) to estimate the probability of occurrence and the occupancy (Iglecia et al. 2012). This was carried out for the two flanking years (eight pairs, species wise and one pair with all vulture locations combined) and repeated for four ecozones. The ecozones without any presence points for a species were excluded from modelling (Hines et al. 2014). The detection rate (P), naïve estimate,

occupancy rate (Ψ) and standard error were extracted from the output file and tabulated as results.

Extent of Occurrence (EOO) and Area of Occupancy (AOO) Estimation

Estimation of EOO and AOO was done using Geospatial Conservation Assessment Tool (GeoCAT) which is an open source, browser-based tool that performs rapid geospatial analysis for Red List assessment. This was developed to utilize spatially referenced primary occurrence data in which the analysis focused on two aspects of the geographic range of a taxon: the EOO and the AOO. These metrics form part of the IUCN Red List categories and criteria. The presence location data collected above were used to calculate the EOO and AOO of the eight different species. The scope of assessment was limited to the state of UP in order to get a localized realistic picture of how the different species were faring in the state. The presence points were uploaded in.csv form in GeoCAT (<https://geocat.kew.org/>) to get the results on these two parameters for conservation status assessment (Bachman et al. 2011). GeoCAT output was in the form of EOO polygon, EOO and AOO areas, and corresponding conservation statuses.

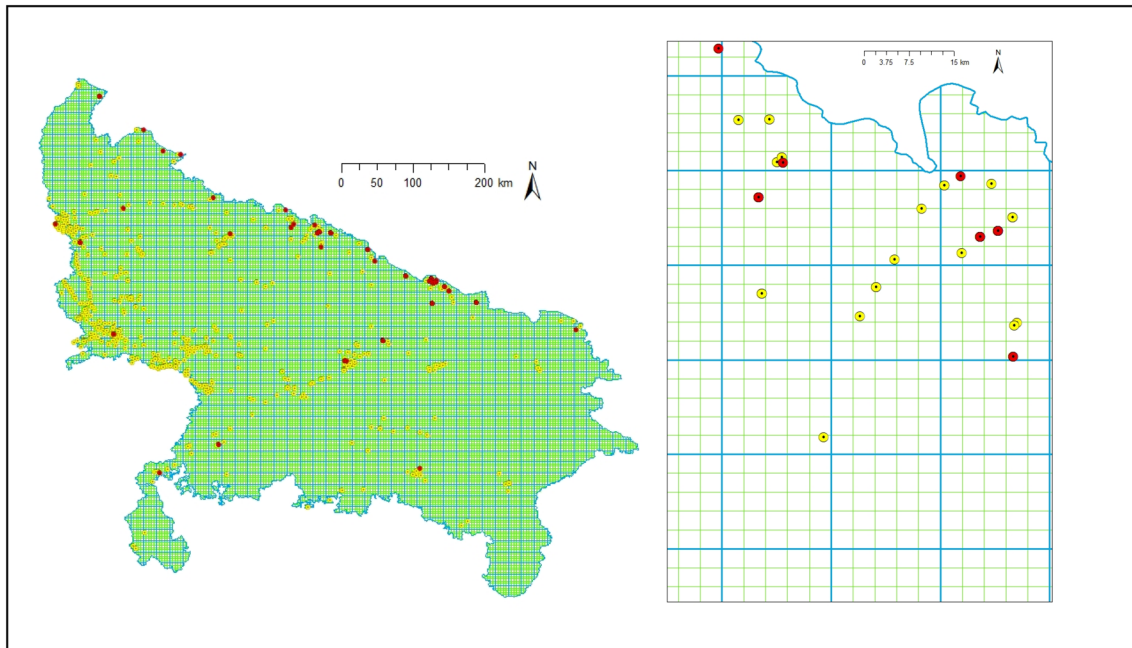


Fig. 3 Map of Uttar Pradesh with fishnet and vulture locations used in occupancy modelling on the left. Zoomed portion of fishnet showing survey sites (blue boxes of 250 km²) and replicates (green boxes

of 10 km²) with vulture sightings (red circles = migratory species, yellow circles = resident species) on the right

Vulture Population Estimation

In order to estimate the decadal change in vulture population, baseline data of 2010 was taken from Jha (2015) estimated by the synchronised count method. For 2020 population, the ‘density per unit suitable area’ method suggested by Zeng et al. (2015) was used. Density was taken from Jha (2022) and suitable area was calculated using MaxEnt, discussed in the next section.

Suitable Habitats Estimation

Species distribution modelling, using MaxEnt algorithm (Phillips et al. 2006), was done to estimate the habitat suitability following Jha and Jha (2021). The chosen model evaluating parameter was Area under curve (AUC) as adopted by several previous researchers (Mori et al. 2020; Anand et al. 2021 etc.). However, Li et al. (2020) suggested using more than one accuracy measure for reliability of SDMs predictions. Therefore, TSS (True skill statistics) and Boyce index were considered for better reflection of model performance as suggested by Allouche et al. (2006) and Hirzel et al. (2006). Accordingly, these values were computed using SSDM (Schmitt et al. 2017) and modEvA (Barbosa et al. 2013) packages in R, respectively. Standard environmental variables (Fick and Hijmans 2017), NDVI (Didan 2015), elevation (USGS EROS 2018), and land use

land cover (Buchhorn et al. 2020) (downloaded from www.worldclim.org and www.earthexplorer.usgs.gov, respectively) were used as input variables along with presence locations. These layers were resampled at 30 arc second spatial resolution. Additionally, original LULC classes provided by Buchhorn et al. (2020) were reclassified into six categories suited to this study. Moreover, in order to remove uncertainties and improve model performance, duplicate removal followed by spatial rarefaction of the occurrence points was carried out, beforehand. Pearson correlation test at ± 0.7 threshold was also carried out to remove highly correlated environmental variables using the “Remove highly correlated variables” tool of SDM toolbox (Brown et al. 2017). For further improvement of the models, bias file was prepared using the “Correcting latitudinal background selection biases” tool of SDM toolbox (Brown et al. 2017). This was done to minimize overfitting and to avoid sampling habitat outside of a species’ known occurrence and account for collection sampling biases with coordinate data (Brown et al. 2017).

Area suitability maps (unsuitable 0–0.3, moderately suitable 0.3–0.6, and highly suitable 0.6–1) were prepared from MaxEnt index maps using ArcGIS 10.5. Extent of occupancy polygons were superimposed on the area suitability maps to find out Potential (outside polygon) and Actual (within polygon) suitable areas in terms of concurrent occupancy.

Results

All the eight species (CV, EV, EG, HG, IV, RHV, SBV and WRV) reported earlier by Grimmett and Inskipp (2003) from the study area were recorded in both 2010 as well as 2020 surveys showing the same species richness over ten years. Some of the photographs recorded during the study are presented in Appendix (Supplementary Fig. 1).

Occupancy modelling

Naïve estimate, occupancy and detection probability of vulture species in UP resulting from occupancy modelling in 2010 and 2020 are presented in Table 2. Naïve estimates ranged between 0.0009 and 0.0723 in 2010 and 0.0018 and 0.0997 in 2020. The trend of change over ten years was mixed: increase in all vultures, EV, EG, and RHV and decrease in CV, HG, IV, SBV, and WRV. Detection probability (P) ranged from 0.022 to 0.065 in 2010 and from 0.017 to 0.054. Naïve estimate and occupancy changed in both the surveys in the case of all vultures, EV, HG, and WRV but CV, EG, IV and RHV. In the 2010 survey the change varied from 19% (WRV) to 71% (HG) while in 2020 survey from 32% (all vultures) to 175% (HG). Indian Vulture showed 129% change only once in the 2010 survey.

However, the decadal change in the occupancy (ψ) of the eight vultures were recorded in three categories: gain (increase in occupancy), loss (decrease in occupancy) and not-determined. The overall vulture occupancy area in UP increased from 8.87 to 13.24%. Egyptian Vulture (3.88–11.25%) and HG (2.68–3.28%) also showed an increase in occupancy area. Indian Vulture (2.09 to < 1%) and WRV (4.25–2.37%) showed a decrease in occupancy. The change in occupancy was not determined for CV, EG, RHV and SBV due to the small sample size in the relatively large study area. In order to overcome this issue,

ecozone wise occupancy modelling results (Supplementary Tables 1–4) are discussed below.

In the Gangetic ecozone in 2010, EV and WRV were detected but in 2020 EG was new detection along with EV. Egyptian Vulture showed occupancy increase from 4.73 to 10.97% in the decade (Supplementary Table 1). White-rumped Vulture showed a loss in occupancy area as it was not detected in 2020 (< 1 to 0%). Eurasian Griffon, a new detection in this ecozone had < 1% occupancy area. However, the overall vulture occupancy increased from 4.95% to 10.97%. In the Semi-Arid ecozone, occupancy for EV and all vultures were found to increase from 12.38% to 31.19% (Supplementary Table 2). The other seven species recorded in UP were not detected in either of the two timeframes: 2010 and 2020 surveys. However, this region showed the highest vulture occupancy in 2020. In the Tarai ecozone, all species were recorded except IV. The overall vulture occupancy in this ecozone declined marginally from 11.83 to 11.18% (Supplementary Table 3). Cinereous Vulture (2.72–1.84%), SBV (2.72 to < 1%) and WRV (11.62–6.29%) also recorded a significant decline in occupancy over the decade. However, EV (< 1 to 10.7%) and HG (8.42–10.31%) recorded a substantial increase. In the Vindhyan-Bundelkhand ecozone the overall vulture occupancy increased from 10.97–13.07% (Supplementary Table 4). This was largely due to the gain in EV (0–7.64%). Indian Vulture showed a loss of occupancy (8.19–5.51%).

Table 3 depicts the ecozone-wise decadal change in occupancy of vultures in UP. Different colours in the cells showed occupancy status trend in the decade (Green = increase, red = decrease, blue = not determined, pink species not detected). In the case of SBV and IV marked with * in the table it was clear that the species recorded a loss in occupancy (Ψ) but the quantum of loss could not be estimated.

Table 2 Occupancy parameters: the naïve estimate, detection probability (P), occupancy (Ψ) and Standard error (SE) of different species in the entire study area

Species	Uttar Pradesh							
	2010				2020			
	naïve	P	Ψ	SE	naïve	P	Ψ	SE
All Vultures	0.0723	0.0652	0.0887	0.0102	0.0997	0.0545	0.1324	0.0134
Cinereous Vulture	0.0046	0.056	<0.01	0	0.0027	0.0533	<0.01	0
Egyptian Vulture	0.0302	0.0585	0.0388	0.0072	0.0842	0.0537	0.1125	0.0126
Eurasian Griffon	0.0009	0.04	<0.01	0	0.0037	0.04	<0.01	0
Himalayan Griffon	0.0156	0.0341	0.0268	0.0085	0.0119	0.0178	0.0328	0.0171
Indian Vulture	0.0091	0.0227	0.0209	0.0108	0.0046	0.048	<0.01	0
Red-headed Vulture	0.0027	0.04	<0.01	0	0.0046	0.04	<0.01	0
Slender-billed Vulture	0.0046	0.048	<0.01	0	0.0018	0.04	<0.01	0
White-rumped Vulture	0.0357	0.0706	0.0425	0.007	0.0165	0.0463	0.0237	0.0065

Table 3 Change in occupancy (Ψ) in different ecozones over the decade for different species of vulture

Vultures	Gangetic	Semi-Arid	Tarai	Vindhyan-Bundelkhand	Uttar Pradesh
All Vultures	6.02	16.3	0.7	2.1	4.4
Cinereous Vulture	0.0	0.0	0.9	0.0	0.0
Egyptian Vulture	6.2	16.3	0.0	7.6	11.3
Eurasian Griffon	0.0	0.0	0.0	0.0	0.0
Himalayan Griffon	0.0	0.0	1.9	0.0	0.6
Indian Vulture	0.0	0.0	0.0	2.7	0.0*
Red-headed Vulture	0.0	0.0	0.0	0.0	0.0
Slender-billed Vulture	0.0	0.0	0.0*	0.0	0.0*
White-rumped Vulture	0.0	0.0	5.3	0.0	1.9

Extent of Occurrence and Area of Occupancy

The EOO and AOO of each species, for 2010 and 2020, with their prospective categories are given in Table 4. In most of the cases, conservation status assessment in UP were threatened. GeoCAT generated EOO polygons of different species superimposed on habitat maps presented in Figs. 4, 5 and 6 showed varied occupancy of vultures covering one or more ecozones. Indian Vulture, SBV, CV and HG were confined to only one ecozone while WRV, EV and RHV covered all ecozones. Eurasian Griffon occupied only two ecozones. These maps indicated the change in the EOO from 2010 to 2020. The results could be broadly grouped into two categories: (i) where little change was seen (IV and HG) on the map (quantified as $< 4000 \text{ km}^2$) and (ii) where a significant change ($> 4000 \text{ km}^2$) was observed (CV, EV, RHV and WRV).

As regards the change in AOO over the decade, CV, HG, IV, SBV and WRV showed an area reduction, while EG, EV and RHV showed increase in area. However, the conservation category, another parameter of AOO, remained unchanged in CV, HG, IV, RHV and WRV. While SBV showed negative, EV and EG showed positive change. After combining both the AOO parameters, overall all impact in the decade showed improvement in the case of EV and EG, but deterioration in SBV. Remaining vultures (CV, HG, IV,

RHV, WRV) with threatened status still were a cause of concern.

Population Change and Temporal Growth

Population of vulture species varied in the studied years and showed positive growth in a decade's time. The total estimated vulture population for 2020 was 5086 shared by different species: 21 (CV), 2354 (EV), 322 (EG), 14 (HG), 1491 (IV), 59 (RHV), 825 (WRV) and 0 (SBV). However, corresponding figure for 2010 was 2028 (total), 0 (CV), 932 (EV), 0 (EG), 14 (HG), 341 (IV), 16 (RHV), 209 (WRV) and 516 (SBV). Zero population of CV, EG and SBV recorded here indicated non-detection during survey, rather than absence from the study area. Estimated growth rates of four resident species for the decade were found to be 11% (EV), 18% (IV), 15% (RHV) and 17% (WRV) per annum. The growth rate for another resident vulture, SBV, could not be estimated as no data for density was available for this species.

Habitat Suitability

All the projected habitat models returned AUC value between 0.812 and 0.982. TSS and Boyce index values varied between 0.501 and 0.944, and 0.421 and 0.965,

Table 4 Extent of occurrence (EOO) and Area of occupancy (AOO) for 2020 and 2010

Vulture species	2010				2020			
	EOO		AOO		EOO		AOO	
	km ²	Category	km ²	Category	km ²	Category	km ²	Category
Cinereous Vulture	7164	VU	28	EN	857	EN	16	EN
Egyptian Vulture	67,813	LC	268	EN	205,354	LC	736	VU
Eurasian Griffon	0	–	4	CR	12,460	VU	16	EN
Himalayan Griffon	19,768	VU	100	EN	21,059	NT	76	EN
Indian Vulture	17,052	VU	52	EN	20,126	NT	24	EN
Red-headed Vulture	22,700	NT	12	EN	101,042	LC	20	EN
Slender-billed Vulture	2954	EN	24	EN	0	–	8	CR
White-rumped Vulture	214,066	LC	356	EN	105,287	LC	128	EN

VU Vulnerable, LC Least concern, NT Near threatened, EN Endangered, CR Critically endangered. The 'Category' is only indicative and needs to be further backed up by population studies

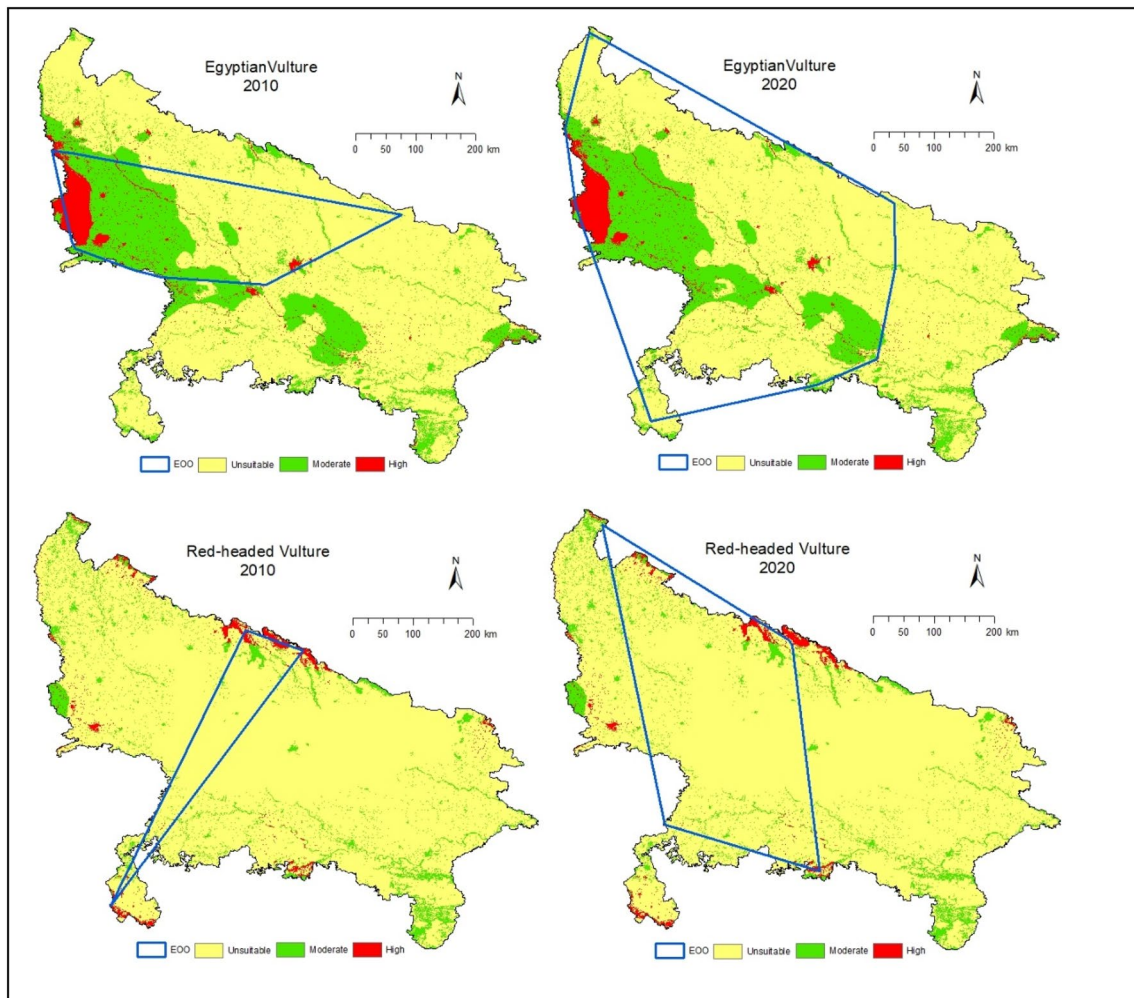


Fig. 4 Maps showing the Extent of Occurrence (blue polygons) of resident non-*Gyps* vultures for 2010 and 2020. Coloured area in the background indicate suitable and unsuitable habitat for the decade

respectively. Species wise model evaluator values and Boyce index chart are presented in Supplementary Table 5 and Supplementary Fig. 2, respectively. MaxEnt predicted unsuitable and suitable (moderate and high) area, for vulture habitation during the decade, is presented in Table 5. The outcome was verified on the ground supported by expert opinion. Suitable habitat area for different vulture species varied and found in following decreasing order: EV (27.7%), EG (18.1%), IV (10.5%), HG (9.6%), WRV (8.7%), RHV (8.7%), CV (8.4%) and SBV (4.8%). Such area falling within and outside the EOO polygon, were considered actual- (inside polygon) and potential- (outside polygon) suitable area, respectively (also see Figs. 3, 4 and 5). However, actual and potential suitable area (both moderate and high) differed after a decade due to varied EOO by different species. Actual suitable area over the decade decreased in CV (1859 km²), HG (3148 km²), IV (292 km²), and WRV (6330 km²) while it increased in EV (23,783 km²), and RHV (3633 km²). Similarly, potential

suitable area decreased in EV (23,774 km²), and RHV (3633 km²) but increased in CV (1860 km²), HG (3148 km²), IV (293 km²), and WRV (6330 km²).

Discussion

The species richness over the decade did not change in Gangetic, Tarai and Semi-Arid ecozones, but the species recorded in the Gangetic ecozone changed. This could be due to inter-ecozone movement of the vultures which concurred with the local movement of vultures reported earlier in central India (Jha 2017) and across the Indo-Nepal border (Pokhrel 2021). Sighting of EG in 2020 was new in the Gangetic ecozone which is possible due to the migratory nature of the species (Campbell 2015; Botha et al. 2017). Its main guiding force in the wintering area is safe roosting sites and/or food. This may have caused it to stray farther than its

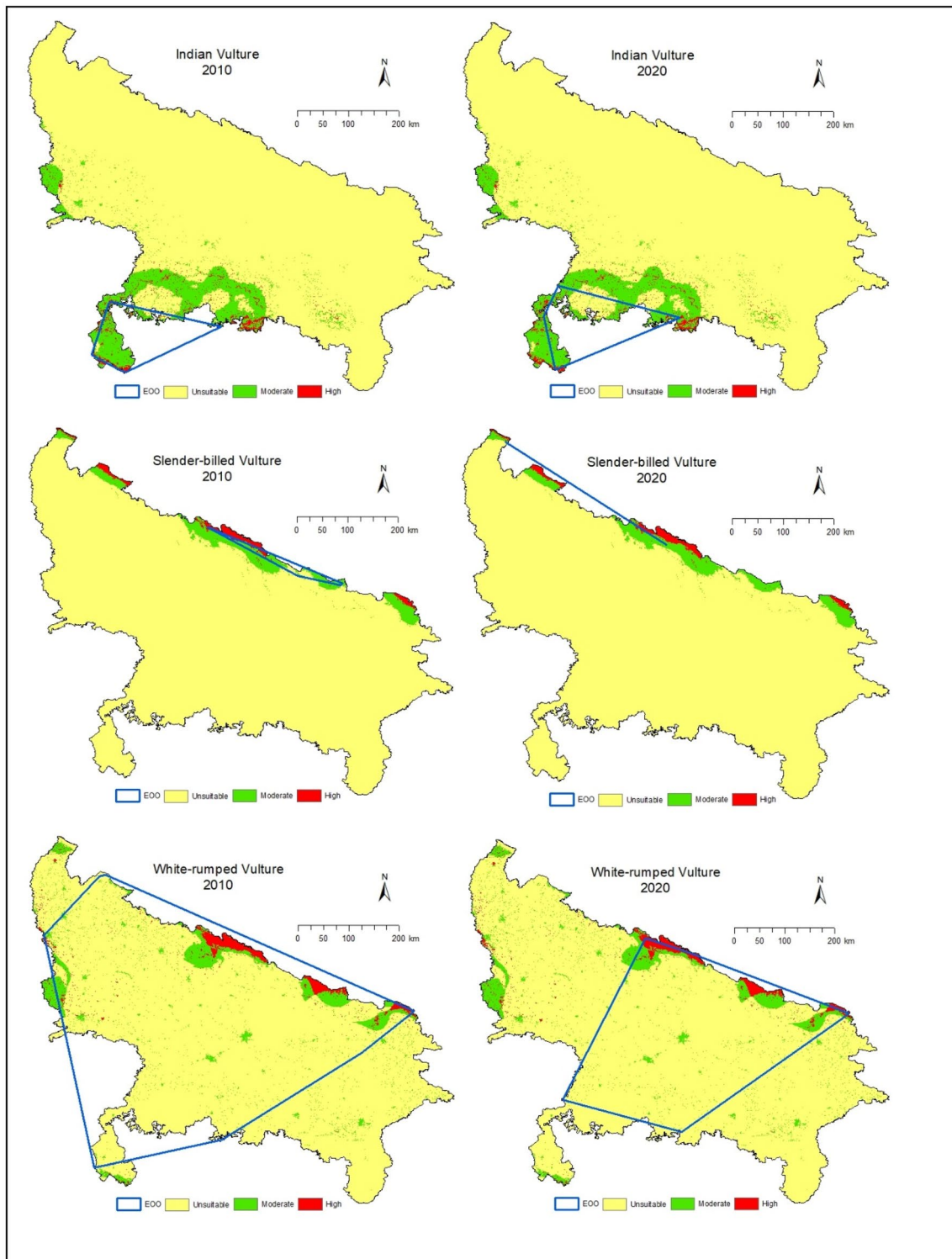


Fig. 5 Maps showing the Extent of occurrence (blue polygons) of resident *Gyps* vultures for 2010 and 2020. The EOO for 2020 in the figure, the case of Slender-billed Vulture, on the middle-right could

not be shown/calculated due to the lack of sufficient data. Coloured area in the background indicate suitable and unsuitable habitat for the decade

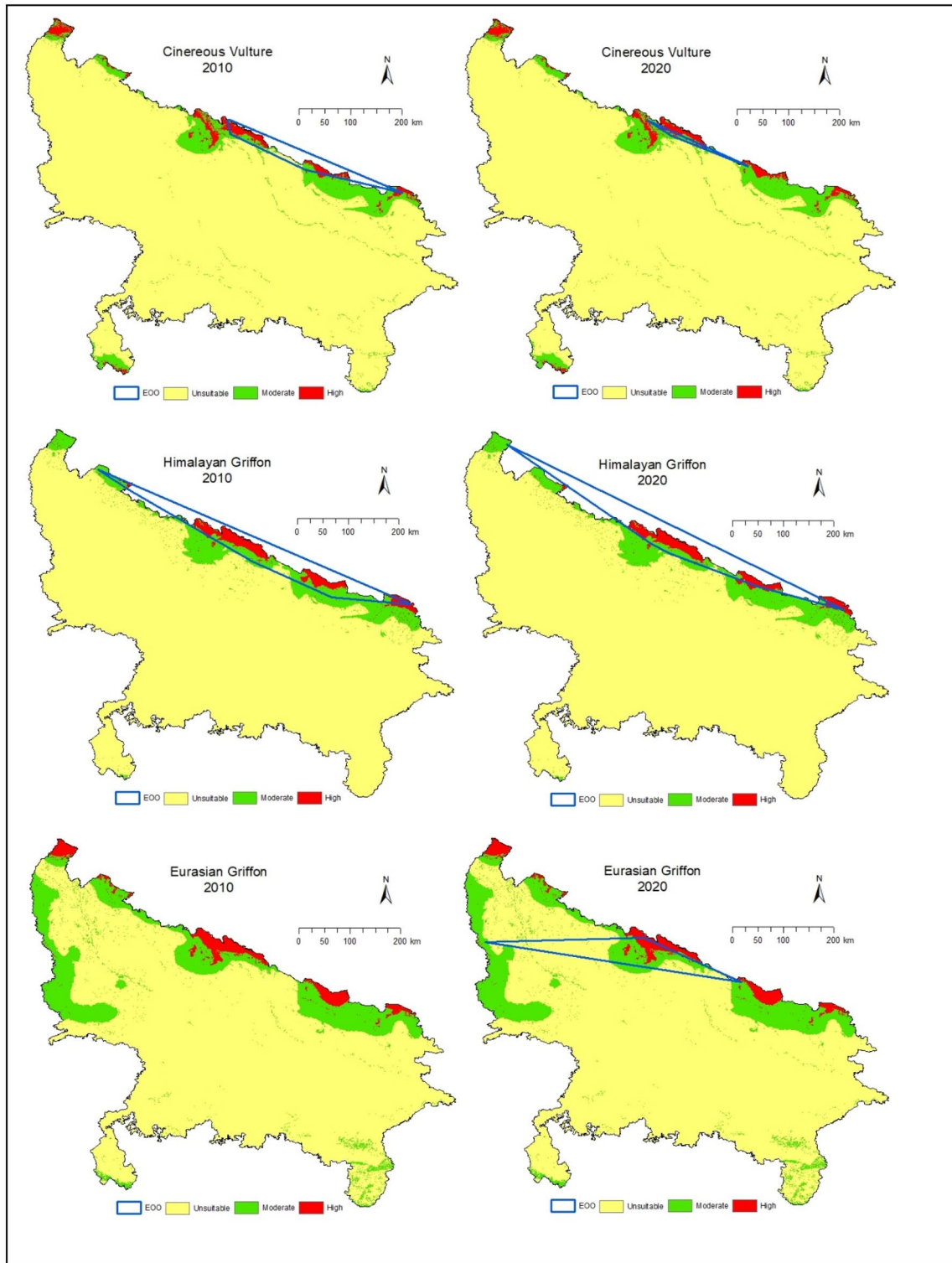


Fig. 6 Maps showing the Extent of occurrence (blue polygons) of migratory vultures for 2010 and 2020. No demarcation of EOO can be noticed in the figure on the bottom-left, case of Eurasian Griffon,

due to no-recording of this vulture during the survey. Coloured area in the background indicate suitable and unsuitable habitat for the decade

Table 5 Habitat suitability area (km²) distribution in Uttar Pradesh (Actual and potential area are within and outside EOO polygon). Dash (–) indicates not determined area in particular year due to no/limited sighting of vultures

Vultures' species	Suitability Class	2010		2020		Total Area
		Actual	Potential	Actual	Potential	
Cinereous Vulture	Unsuitable	404	220,176	68	220,512	220,580
	Moderate	998	14,651	441	15,208	15,649
	High	1553	3147	251	4450	4701
Eurasian Griffon	Unsuitable	–	–	6923	93,008	197,356
	Moderate	–	–	4513	103,774	36,544
	High	–	–	1518	31,193	7030
Egyptian Vulture	Unsuitable	33,582	140,696	111,247	63,030	174,278
	Moderate	26,314	31,111	47,896	9529	57,425
	High	6250	2978	8450	777	9227
Himalayan Griffon	Unsuitable	491	217,330	126	217,695	217,821
	Moderate	4588	13,430	2000	16,018	18,018
	High	4162	929	3602	1489	5091
Indian Vulture	Unsuitable	517	215,172	2866	212,824	215,690
	Moderate	4585	17,791	4474	17,903	22,376
	High	709	2156	528	2336	2864
Red-Headed Vulture	Unsuitable	20,443	199,539	86,582	133,400	219,982
	Moderate	1058	15,287	3845	12,500	16,345
	High	627	3976	1474	3130	4604
Slender-billed Vulture	Unsuitable	501	228,865	–	–	229,366
	Moderate	1458	7573	–	–	9031
	High	308	2225	–	–	2533
White-rumped Vulture	Unsuitable	156,525	63,456	91,402	128,579	219,981
	Moderate	12,074	3894	7199	8769	15,968
	High	4417	564	2961	2019	4981

previously recorded range (Sullivan et al. 2009). Jha (2017) has also reported EG beyond the southern boundary of UP on lower latitudes. However, the non-detection of a resident, WRV, which might have had a breeding population in this region, needs to be investigated further. This must be done to ascertain if the disappearance from this ecozone is merely a blip or an indicator of a more serious trend of decrease in population. Additionally, a hypothesis of non-recovery of the population of this vulture from diclofenac shock also requires attention, since diclofenac is not completely out of the market (Richards et al. 2017; Galligan et al. 2020; Jha et al. 2021). The Vindhyan-Bundelkhand ecozone showed a presence of EV in 2020 which was not recorded previously in the baseline study (Jha 2015). Expansion in occupancy in the ecozone with large patches of suitable area is an encouraging sign for this globally threatened vulture. Additionally, the presence of this species on a semi-urban garbage dump during the 2020 survey showed foraging plasticity, recorded elsewhere also (Thakur and Narang 2012; Bahadur et al. 2019). This vulture, despite its cliff nesting nature, was found in all ecozones, even in those without cliffs. This may also be attributed to its ecological plasticity (Oppel et al. 2017; Bahadur et al. 2019). Location specificity of IV in Vindhyan-Bundelkhand ecozone was due to its cliff nesting,

non-ecologically plastic, nature and presence of cliffs only in this ecozone (Jha 2017). Similarly, the specificity of tree nesting in moist area of SBV may be attributed to the presence of moist conditions and tall nesting trees in the Tarai ecozone. The presence of WRV and RHV, adapted to varied environmental conditions, was more wide spread.

Occupancy Estimation

Single season occupancy models, run in the present study, assumed that (1) the system was closed to changes in occupancy during sampling, (2) the species was not falsely detected and (3) species detections were independent (Iglécia et al. 2012). The first condition was met as different vulture species are known to show site fidelity (García-Ripolles et al. 2010; Freund et al. 2017; Majgaonkar 2018). The second condition was considered fulfilled as the data incorporated in the study was either collected by experts or was classified as “research-grade” in the case of citizen science. The third condition was met by ensuring spatial independence of data with the help of shelter sites, defined as squares with an area of 10 km², and marked as 1 (detected) irrespective of the number of sightings within one shelter site.

The value of improved occupancy (13.2%) of all vultures (superspecies) in the present study is comparable to the findings (14.3–15.2%) in Madhya Pradesh (Jha et al. 2020). However, detection probability recorded for all vultures (0.054–0.065) was much lower to other long ranging rare species with wide distribution like Siberian crane (0.48, Byskatova et al. 2016) and Philippine serpent eagle (0.35, Concepcion 2017). Though the detection probability was low over space and time, naïve estimates and occupancy rate (ψ) always varied in different species and ecozones showing the former value lesser than the latter. Naïve estimates gave simple presence without compensating for non-detectability. Occupancy expressed as a percentage, calculated the proportion of probable area occupied by the different species in the entire state. Slight increase in the occupancy (ψ) from the naïve estimate was due to adjustment for detectability. This was true for all the species where occupancy estimation was calculated (EV, HG, IV and WRV). This trend was further strengthened in the analysis for each ecozone. Yoccoz et al. (2001) also confirmed that a major source of variation in presence-absence studies can arise from detectability. MacKenzie et al., (2006) stated that the identification of a temporarily unoccupied site as vacant can lead to misinformed management decisions, therefore, occupancy models are designed to accommodate imperfect detection (MacKenzie et al. 2002).

Mostly the probable area occupied was found to increase or decrease over the decade except in the cases where it could not be determined. An increase in area occupied by a particular species (e.g., HG and IV) in a particular ecozone (Tarai and Vindhyan-Bundelkhand, respectively) indicated its preference for that locality. This may be correlated with increase in number and spread of that vulture in particular area, assuming that occupancy represented the abundance of a species (IUCN 2019). The presence of highest number of species was recorded in the Tarai ecozone followed by the Vindhyan-Bundelkhand ecozone, Gangetic ecozone and Semi-Arid ecozone. A possible reason for this could be safe shelter and foraging abundance in the moist deciduous forests of the Tarai ecozone. Jha and Jha (2021) and Jha et al. (2020) have also reported the occurrence of 87% of vultures in forested area vis a vis 13% in agriculture area in a study conducted in central India which has some similarity in landscape and forest types. Prakash et al. (2012; 2017) have also recorded similar findings i.e., major presence of vultures in forests as compared to outside forest area in other parts of India.

Extent of Occurrence and Area of Occupancy

The threat categories of six vultures (CV, EV, HG, IV, RHV, WRV) in terms of EOO found to have changed over the decade can be used to determine the degree of risk from

threatening factors, such as heatwaves, drought, invasive species and habitat degradation among others (IUCN 2019). Since these vultures (exception CV) did not fall in the category of endangered and critically endangered species it may be concluded that they have an adequate expanse available within UP. However, it is essential to mark that the scope of assessment of this analysis was limited to the study area of UP and the categories assigned by the GeoCAT tool are only indicative and need rigorous studies of population to be ascertained. As the maps suggested, EOO covered area outside UP (neighbouring Madhya Pradesh, Rajasthan and Nepal) was due to its calculation using a minimum convex polygon (Burgman and Fox 2003). This also conformed to the behaviour of mobile organisms which are not restricted by political borders. Nevertheless, the AOO in terms of conservation status category and area occupied was found to have improved for RHV, EG and EV over the decade but declined for the remaining vultures having different implications on safety like insurance effect in terms of the number of patches available (IUCN 2019). By using the GeoCAT assigned categories in this study, it may be surmised that vultures within UP are present in a few small patches which may not be sufficient to safeguard a species in the case of an extinction event. This may have serious repercussions on the existing population of these species in the state.

Habitat Suitability

Predicted habitats were very useful and considered suitable for planning purposes (Pearce and Ferrier 2000) due to good to excellent category prediction power (Swets 1988; Hirzel et al. 2006; Rew et al. 2020) by all the three model evaluators (AUC, TSS and Boyce index). The overall habitat suitability for UP was treated as constant based on two assumptions. Firstly, the changes in climate over ten years would be negligible. Secondly, significant category changes in land cover would not have occurred in the forests as almost all forests in UP are protected. Further, the changes in other categories of landcover would not be significant enough to drastically alter habitat suitability. Therefore, in order to study the decadal change in suitable habitat of different vulture species, the outputs of SDM and EOO projection were combined. The change in actual suitable area (suitable area inside EOO polygon) represented a more accurate picture of changing habitation of vultures over the decade (from 2010 to 2020).

Egyptian Vulture prospered in the state, showing a major expansion within the available suitable area. This is in tune with its adaptation to anthropogenic interferences in its habitat (Plaza and Lambertucci 2017; Ballejo et al. 2021). Contrastingly, CV, HG, IV, SBV and WRV did not show such adaptation and further shrunk in their spread in available habitat. In this regard, an increase in the potential- *vis a vis* actual- suitable area pointed towards the under-utilization

of suitable habitat. This reflected abandonment of area due anthropogenic disturbances or climatic anomalies such as thunderstorms, flash floods, forest fires etc. prevalent in the forest during the studied decade. This warrants further, more localized, studies in suitable areas to pin point the cause behind the reduction in occupancy of suitable area and finally choose for appropriate interventions to manage the population for recovery.

Decadal Change Per Se

Overall, in the last decade in UP, the vulture population had seen large gains (5086) in terms of projected numbers, using the 2010 reference population (2028) as the bench mark (Jha 2015). This growth amounts to approximately 11% increase per annum which seems very high considering old world vultures as slow breeders with low growth rates (Donazar and Ceballos 1989). The increase in occupancy (Ψ) was also in tune with the data from the population estimation of all vultures together as “superspecies”. However, this was not very insightful in understanding the individual fate of different vulture species.

Therefore, when considered species wise, Egyptian Vulture was the most widespread among all vulture species as it had been recorded in all four ecozones. The occupancy (Ψ) and population were also estimated to have increased in the last ten years. This is an encouraging sign of possible vulture recovery since 10–17% growth in population is considered very healthy in long lived, large flying birds (Archibald et al. 1981; Johnsgaard 1983). However, the study by UPFD and BNHS (2021) estimating 24,671 individuals indicating an annual growth rate of 37.5% in the past ten years is in stark contrast with the reported annual growth of EV by 7–8% (Kamboj et al. 2016; Jha et al. 2020). Although this large population may be debatable, detection in new areas coupled with the availability of potential suitable habitat much larger than actual suitable habitat suggested environmental suitability with minimized threats for EV.

Indian Vulture was only recorded in the cliffs on the banks of the river Betwa in the Vindhyan-Bundelkhand region which is known for its hot and dry climate, as compared to the rest of the state. Its occupancy (Ψ) in the state and this ecozone underwent a decline over the decade. Contrastingly, the estimated population was found to have increased. This indicated that the population was concentrated in small areas. Since, EOO and AOO also did not show any significant improvements over the decade this limited spread puts the population at risk of decline if faced with severe threats like climatic anomalies. However, another study by McClure et al. (2021) reported a decline in the population trend of IV in the neighbouring state of Rajasthan.

White-rumped Vulture had shown a decline in occupancy (Ψ) in the entire study area but the estimated population

was found to have grown. However, a reduction in EOO over a decade and the sharp decline in detectability of this species during the 2020 surveys may be signaling a slow recovery and concentration of population in remote areas in the aftermath of the diclofenac shock. This growth pattern also agreed with the reports by Prakash et al. (2012; 2017).

The analysis for a decadal change in RHV populations and occupancy (Ψ) was not very insightful due to its limited sightings. The reason for low sightings of RHV could be due to their low numbers as well as the fact that these are solitary birds or found only in pairs around carcasses (Sinha et al. 2017) unlike the *Gyps* vultures which are found in large groups. However, this study estimated the population of the species in the study area which was found to have grown at an annual rate of approximately 25%. Though this growth rate is very high and debatable, expansion of EOO and further availability of potential suitable area indicated a positive future for the species.

Slender-billed Vulture was not spotted on any transect during the course of this study which is similar to the observation by UPFD and BNHS (2021). Its presence, however, was reported in data retrieved from citizen science databases. The occupancy (Ψ) over the past ten years was found to have declined. This indicates a serious concern since this area supported a bulk of this species in the past (Jha 2015). Any threat to the undetected individuals in a narrow belt of suitable habitat in monotypic landscape Tarai could have a serious impact on the future of the whole population.

Decadal change in EG could not be studied due to insufficient baseline data. Cinereous Vulture was only recorded in the Tarai ecozone at limited locations, where the occupancy (Ψ) had declined by around 1%. However, HG had an improved status of occupancy (Ψ) as well as population. It showed an increase in occupancy and numbers in the entire state, especially in the Tarai ecozone. This was strongly backed by field observations and interviews of resource persons. This could be seen as a positive sign not only for HG, but also for the two other migratory species, for which insufficient data was available. Since the three species are almost similar in habit and habitat requirement for the duration of November-March, it stood to reason that the other two species may also have received the same benefits from the environmental conditions as HG.

Conclusion

This paper analyses the decadal change in occupancy, population and habitat of threatened vultures in Uttar Pradesh using ecological modelling tools. Trends at the localized level differed from those at the global level. The migratory species showed a positive trend over the decade, however, the trends for the resident species were mixed. The prospects

of Egyptian Vulture are the brightest as it has shown an increase in occupancy, population as well as suitable area. The four critically endangered resident species (Indian Vulture, Red-headed Vulture, Slender-billed Vulture, White-rumped Vulture) require more focused studies as their growth in the past ten years has shown a very slow recovery from the diclofenac shock. This makes it crucial to conserve the existing population in order to protect from further setbacks. Therefore, the suitable areas delineated in this study must be used for management interventions, such as creation of Vulture Safe Zones, for safeguarding the future of these vulnerable birds.

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Data availability All data generated or analysed during this study are included in this article.

Declarations

Competing interest The authors have no relevant financial or non-financial interests to disclose.

Ethical statement This is an observational study. All the guidelines were observed for the care of animals during the study.

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