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Research article

Unraveling the unknown: Adaptive spatial planning to enhance climate resilience for the endangered Swamp Grass-babbler (*Laticilla cinerascens*) with habitat connectivity and complexity approach

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ABSTRACT

The endangered and poorly known Swamp Grass-babbler, *Laticilla cinerascens* (Passeriformes: Pellorneidae), confronts critical threats and vulnerability due to its specific habitat requirements and restricted populations in the northeastern region of the Indian Subcontinent. This study investigates the distribution of the species, habitat quality, geometry and shape complexity of connectivity among the protected areas (PAs), and responses to climate change in Northeast India under different climate change pathways by utilizing ensemble distribution models, and ecological metrics. From the total distribution extent (1,42,000 km^2), approximately 9366 km^2 (6.59 %) is identified as the suitable habitat for this threatened species. Historically centered around Dibru Saikhowa National Park (DSNP), the species faced a drastic decline due to anthropogenic activities and alteration in land use and lover cover. The study also reveals a significant decline in suitable habitat for *L. cinerascens* in future climate scenarios, with alarming reductions under SSP126 (>10 % in the timeframe 2041–2060 and > 30 % from 2061 to 2080), SSP245 (>90 % in both time periods), and SSP585 (>90 % in both timeframes) from the present scenario. At present, DSNP has the most suitable habitat within the distribution range but is projected to decline (>90 %) under more severe climate change scenarios, as observed in other PAs. Landscape fragmentation analysis indicates a shift in habitat geometry, highlighting the intricate impact of climate change. It predicts a substantial 343 % increase (in the SSP126) in small habitat patches in the future. Connectivity analysis among PAs shows a significant shift, with a decline exceeding 20 %. The analysis of shape complexity and connectivity geometry reveals a significant increase of over 220 % in the fragmentation of connectivity among PAs between 2061 and 2080 under the SSP585 climate change scenario compared to the present conditions. The study underscores the urgent need for conservation actions, emphasizing the

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complex interplay of climate change, habitat suitability, and fragmentation. Prioritizing PAs with suitable habitats and assessing their connectivity is crucial. Adaptive management strategies are essential to address ongoing environmental changes and safeguard biodiversity. Future research in critical areas is needed to establish long-term monitoring programs to lead/extend effective conservation strategies.

1. Introduction

In the realm of world biodiversity, the Indian Subcontinent is recognized for its exceptional species diversity and ecosystem services [1]. Among the global spectrum of 75 bird families, this region boasts an impressive record with 48 families within its extent, thereby making a significant contribution of over 13 % to the overall global bird population [2–4]. Astonishingly, the northeastern region of India is home to a remarkable diversity of 800 avian species, with expectations of further discoveries in the coming decades [5]. However, recent years have witnessed an alarming trend of escalating global biodiversity loss, leading to approximately 1400 bird species being at immediate risk of extinction [6]. Recent evidences also indicates that various taxonomic groups, including birds, are already responding to global warming [7–10]. This critical situation is further exacerbated by habitat destruction driven by climate change [11]. Nevertheless, such habitat loss poses a significant threat to India's bird diversity, expected to persist in coming decades [12]. Although the impact of climate on biodiversity is widely acknowledged, there remains a necessity to enhance the understanding of specific species and ecosystems most susceptible to its effects, as well as underlying conditions that render them vulnerable [13]. Some research indicates that factors beyond climate change, such as the extent and accessibility of suitable land cover, may influence the response of species [14–16].

Additionally, simulation studies have also shown that habitat loss can impede a species' capacity to adapt to changing climatic conditions [17]. On the contrary, an expansion of suitable land cover has been shown to mitigate species extinction rates when compared to the worsening impacts of climate change [18]. Nevertheless, empirical evidence on avian communities remains limited, as studies that consider the combined effects of land cover and climatic conditions are relatively rare [16,19,20].

In particular, climate change possesses the capacity to influence populations of grassland birds through diverse mechanisms, including the effects of temperature and precipitation on abundance, fitness, and behaviour across multiple spatial and temporal scales [21–23]. Similarly, elevated temperatures and extreme weather events can directly impact variables such as reproduction and habitat selection by inducing thermal stress and causing nest damage [24–26]. Concurrently, alterations in precipitation patterns may modify bird dynamics within their habitats and breeding patterns [27–29]. Considering the complex interplay of mechanisms involved and the projected alterations in climatic parameters, it is crucial to comprehend the susceptibility of grassland birds [30]. Further, species occupying restricted habitats may encounter elevated vulnerability, attributed to the heightened risk of extinction and limited options for spatial refuge from their threats. Moreover, their vulnerability may arise from the fact that small, geographically confined populations are more prone to local extinction [31]. Nevertheless, to address ecological challenges impacting biodiversity, biological corridors also play a pivotal role by connecting habitat patches and facilitating genetic exchange among populations [32]. These corridors serve as vital mechanisms for mitigating demographic uncertainties and buffering against the effects of climate. However, anticipated shifts in geographic isotherms may result in the disappearance of these movement corridors and the loss of suitable habitats for various species [33]. Hence, it is necessary to investigate the connectivity corridors within the framework of climate dynamics, taking into account both their temporal dynamics and habitat projection models [34].

Among the 182 endangered avian species within the Indian subcontinent [35], the lesser-known Swamp Grass-babbler, *Laticilla cinerascens*, confronts significant threats in its extent [36]. This species was initially described as *Eurycercus cinerascens* in 1874, based on specimens from Dhubri, Assam (formerly 'Lower Bengal') [37]. However, multiple taxonomic revisions have led to the systematic challenges of this species resulting in numerous reclassifications. Previously, the species was placed with Rufous-vented Grass Babbler (*Laticilla burnesii*) as Long-tailed Grass-Warbler, and later shifted to the genus *Prinia* [38,39]. Subsequently, it was further reclassified based on various distinguishing characteristics, including a thinner bill, shorter tail, less prominent streaking on the upperparts, a generally grayer overall coloration, and grayish undertail coverts instead of rufous [40]. This reclassification was further supported by distinctive song, and behaviour more alike to babblers than prinias or warblers. Unlike other *Prinia* species, this particular species does not produce wing-snapping noises or engage in aerial displays [41,42].

Further, differences in egg color also supported the taxonomic distinction of *L. cinerascens* as compared to other closely related species [40]. Further investigations into the species' phylogeny confirmed in its systematic classification to the genus *Laticilla* within the Pellorneidae family [39]. Historically, *L. cinerascens* was described as commonly known bird in the suitable grassland habitats of Brahmaputra plains during the late 1800s and early 1900s. However, due to the elusive behavior and infrequent sightings, there was a significant gap in records of this species for several decades. This gap can be attributed in part to the challenges associated with surveying its seasonally inundated habitat in the river plains and a general lack of attention given to this species.

The Swamp Grass-babbler is primarily inhabiting in the plains of the Brahmaputra River and its tributaries in northeastern India, its presence is notably localized and occurs at very low population densities due to specific habitat requirements [36,43]. These habitats undergo continual alteration and damage as a result of ongoing changes in river courses and agricultural expansion, significantly impacting the range of this species. Similar threats have been assessed by the IUCN specialist group and categorized the species under 'Endangered' category [36]. This species was historically known from the eastern Nepal (Koshi Tappu Wildlife Reserve), eastern India (Munger, Bihar), southern part of Assam (Cachar) in northeastern India, and Bangladesh (Sylhet) [44]. However, these records lack validation and might potentially result in confusion with the Graceful Prinia (*Prinia gracilis*) [42]. Fortunately, recent sightings and acoustic records of *L. cinerascens* have provided valuable insights into the newly identified locations confined to two adjacent protected areas (PAs) viz., Dibru-Saikhowa National Park (DSNP) in Assam and D'Ering Memorial Wildlife Sanctuary (DMWLS) in Arunachal Pradesh [42]. Therefore, achieving a more comprehensive knowledge of the combined effects of climate change and land cover for this species in both present and historical range will offer deeper insights into the diverse levels of susceptibility as observed in other grassland species [45,46].

Additionally, it is crucial to obtain insights into the current, and anticipated future status of its habitat for effective conservation and management planning [47]. To delineate the occurrence of the species within a specific geographic area, species distribution models (SDMs) play a pivotal role in providing essential information [48]. This approach act as a valuable tool for accurately predicting current habitat conditions and have the capability to forecast future species distributions. They utilize prior knowledge of species occurrences and associated ecological envelopes across both space and time [49], aiding in the development of informed strategies for habitat management and conservation initiatives [50].

Moreover, it is evident that the integration of eco-physiological models has been indispensable in SDM projections for numerous vertebrate species, including birds, to better understand range shifts in response to climate change [51–54]. Consequently, SDM can be employed to identify potential habitats in both present and future scenarios, with the objective of aiding prioritization and informing species-specific conservation strategies [55].

Therefore, in present study an SDM was developed for the Swamp Grass-babbler aimed to evaluate the current distribution using an ensemble approach and project its future distribution. Furthermore, the present study also analyzed the fragmentation in the suitable areas in present and future scenarios. Moreover, the suitable areas and connectivity within the PAs adjacent to the extent of the studied species were also assessed for conservation prioritization, given their governance and protection under governmental jurisdiction. This assessment facilitates the targeted allocation of conservation endeavors aimed at both permanent and seasonally impacted grassland habitats in accordance with species extent.

2. Materials and Methods

2.1. Study area

The present distribution of the Swamp Grass-babbler encompasses the entire Brahmaputra floodplain in northeast India. Its range is

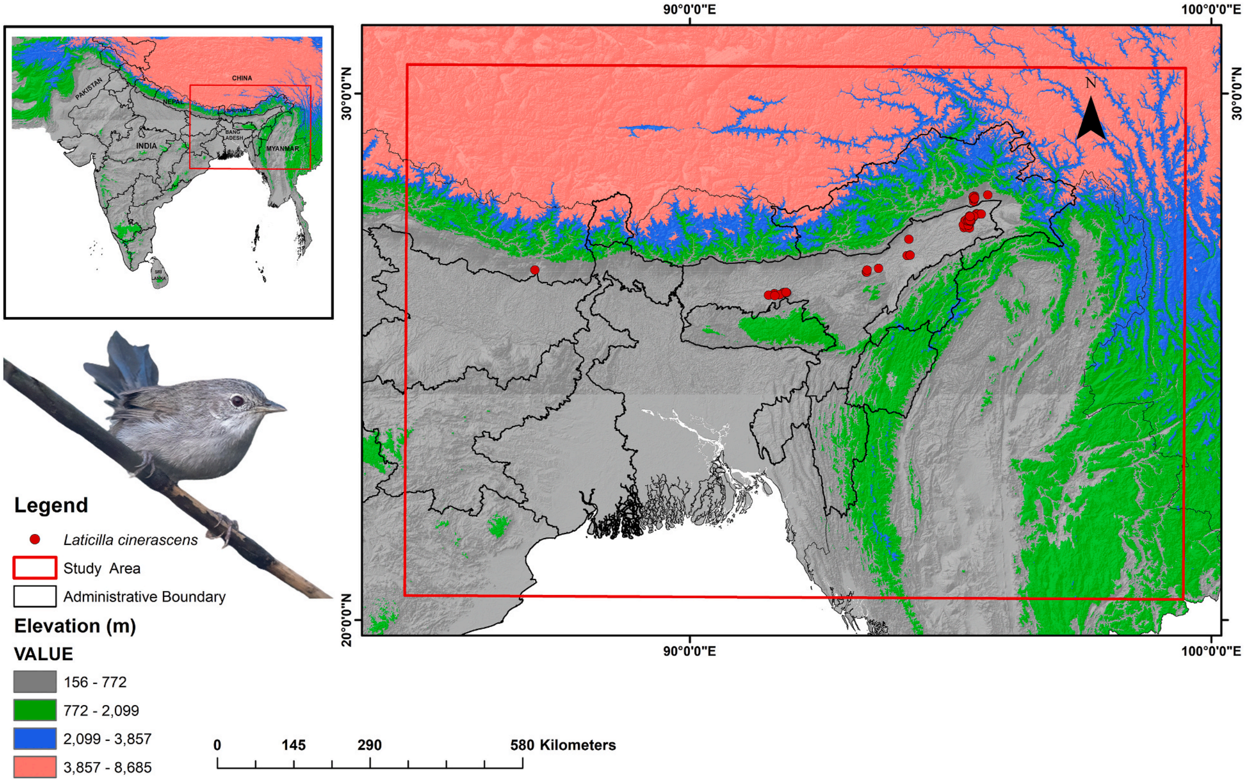

Fig. 1. Map showing the Global Distribution Range and sighting locations of the Swamp Grass-babbler *L. cinerascens*. Color code represents the elevation gradient in the study landscape. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.). Photo Credit: Mr. Rofikul Islam.

extended eastward along the Subansiri River in North Lakhimpur, Assam, situated on the northern bank of the Brahmaputra River. Recent observations have expanded its known range to include Tinsukia and Dibrugarh in Assam, primarily from DSNP, located on the southern bank of river Brahmaputra. Additionally, sightings have also been recorded in the Kamrup district near Guwahati and at the Burachapori Wildlife Sanctuary (BWLS) near Majuli in Assam (Fig. 1). Furthermore, occurrences of the species have been documented in the Siang (DMWLS) and Dibang river valleys in Arunachal Pradesh [42]. Hence, the study area was determined based on both the IUCN extant (Brahmaputra plains) and historical ranges (eastern Nepal, eastern India, Southern Assam, and Bangladesh) documented in previous literatures [36,41,42,44]. This approach aimed to assess the extent habitats and possibly extant (resident) in the entire landscape as well as to analyze the habitat alteration induced by climate change.

2.2. Species occurrence data

The primary occurrence sources utilized in this scientific study comprised data obtained through field visits and secondary citizen science platforms, including ebird ($n = 477$) (https://ebird.org/home), Global Biodiversity Information Facility (GBIF) ($n = 223$) (https://doi.org/10.15468/dl.5e8har), and data retrieved from evaluated scientific literature ($n = 5$) [54,56,57]. The field survey was conducted between January and December 2022 ($n = 10$) at Maguri-Matapung Beel and DSNP. The location points were collected using the Garmin GPS eTrex 10. In total, 715 occurrence points were aggregated from various sources within the northeast India for the purpose of conducting the SDM (Fig. 1). The final dataset encompassed records spanning from 1977 to 2023. One occurrence point (26.643 N and 87.028 E at Koshi Tappu Wildlife Reserve, Nepal) was excluded from the analysis due to the lack of definitive evidence (photographs or acoustic recordings) [41,42]. Finally, a total of 133 location points were selected after spatial rarefication at 1 km^2 using the spatial rarefy option in SDM Toolbox v2.4 [58].

2.3. Model covariates

In consideration of the ecological needs of *L. cinerascens*, the study conducted an initial screening of significant variables that could potentially influence the prediction of suitable habitats [59]. These variables encompassed climatic conditions, specifically the 19 standard bioclimatic variables sourced from Worldclim, Version 2.0 (https://www.worldclim.org/) [60]. Additionally, the analysis factored in land use and land cover (LULC) data obtained from the Copernicus Global Land Service (https://lcviewer.vito.be/download) to examine the impact of individual LULC classes [61]. The built-up area was separated from the LULC data obtained from the Copernicus Global Land Service. To assess the influence of water availability on the species, the distance to major water bodies was calculated using the Euclidian distance function in ArcGIS 10.6 from the data obtained from DIVA-GIS (https://www.diva-gis.org/gdata) [62]. Topographic variables, such as elevation and aspect, were derived from the 90-m Shuttle Radar Topography Mission (SRTM) data (http://srtm.csi.cgiar.org/srtmdata/). All predictors were resampled at a spatial resolution of 1 km^2 through the spatial analysis tool within ArcGIS 10.6. Spatial multicollinearity among the predictors was assessed using SDM Toolbox v2.4, and variables exhibiting a Pearson's correlation coefficient $r > \pm 0.8$ (Table S1) were excluded from the final model [63]. Furthermore, to project climate change scenarios under three distinct Shared Socio-economic Pathways (SSP)—namely ssp126, ssp245, and ssp585—for the periods 2041–2060 and 2061–2080, the study employed the General Circulation Model (GCM) Hadley Centre Global Environment Model in the Global Coupled Configuration 3.1 (HadGEM3-GC31 LL), a part of the UK's contribution to the sixth Coupled Model Intercomparison Project (CMIP6) [64]. Notably, for this analysis, non-climatic raster data remained constant to evaluate the isolated effect of climate change on the study's objectives [65].

2.4. Model development and assessment

Utilizing the SSDM package in the R environment version 3.1 [66], the evaluation of the distribution model for the Swamp Grass-babbler involved multiple modeling algorithms. The final distribution model was constructed by employing an ensemble approach. The effectiveness of the ensemble modelling approach in accurately predicting the probability of species presence has been underscored in various studies [50,59,67–70]. Following the completion of the variable selection process, the conversion of variables to the SSDM-supported file format was carried out to assess the probability of the maximum suitable habitat for the study species. A total of 70 % presence data for the species was utilized for model building, while the remaining 30 % was reserved for testing. The SSDM environment was configured with 10 replications, employing SES (Sensitivity-Specificity Equality) as the evaluation metric. Nine model types, namely Generalized Linear Model (GLM), Generalized Additive Model (GAM), Multivariate Adaptive Regression Splines (MARS), Maximum Entropy (MAXENT), Artificial Neural Network (ANN), Support Vector Machine (SVM), Random Forest (RF), Classification Tree Analysis (CTA), and Gradient Boosting Machine (GBM), were employed to establish the habitat suitability of the species. To select the best-fitted model and ultimately construct the ensemble probability surface, an AUC threshold of <0.75 was set. The logistic output format was utilized for calculating the sensitivity analysis for each variable. The validation of the final ensemble model involved the generation of AUC values of ROC (Receiver Operating Characteristic), guiding the model evaluation based on poor (0.6–0.7), normal (0.7–0.8), good (0.8–0.9), and best (0.9–1.0) ranges. The assessment of the final ensemble model for the species was conducted using ENMeval [71], and the evaluation of variable importance was determined by the percentage contribution in the final model.

2.5. Biological connectivity and patch level habitat evaluation

In evaluating the biological connectivity between patches that exhibit high suitability, the circuit model, a commonly employed method for designing animal corridors, was employed [72]. The biological corridor for *L. cinerascens* was simulated by utilizing the Circuitscape toolbox for ArcGIS Ver. 10.6 [72–74]. The conductance surfaces for generating connectivity in the landscape consisted of output probability surfaces derived from the habitat suitability model, considering both present and future habitat conditions [75]. To simplify the computational demands, the connections were constructed using the centroids of highly suitable patches situated within the PAs. Additionally, these same centroids were employed in forecasting the future biological connectivity of the studied species.

2.6. Assessment of habitat quality and shape complexity

The comparative analyses between the suitable areas of *L. cinerascens* for both present and future climatic models were conducted. Class-level metrics, including the number of patches (NP), aggregate index (AI), patch density (PD), largest patch index (LPI), edge density (ED), total edge (TE), and landscape shape index (LSI), were estimated using FRAGSTATS version 4.2.1. These metrics served as indicators for assessing habitat characteristics and the level of fragmentation in the modelled area under current and climatic change scenarios [55].

Further, for the geometric evaluation of the connectivity among the PAs, both Landscape Shape Index (LSI) and Splitting Index (SPLIT) were used. The LSI provides a quantitative measure of landscape configuration and fragmentation, assessing the complexity and irregularity of patch shapes within the landscape. This index is crucial for understanding the spatial arrangement and shape of PAs, and how these factors influence ecological connectivity and habitat continuity of the studied species. In addition, the Splitting Index (SPLIT) has been employed to gauge the degree of isolation and fragmentation of the corridors. It quantifies how the corridor patches are divided and isolated, offering insights into the potential barriers to movement for the species. Combining the insights from both LSI and SPLIT, an extensive evaluation of the effectiveness of current PA connectivity has been conducted.

3. Results

3.1. Species distribution model

The results of the average replicates run of the final ensemble model found an AUC value of 0.97 (Fig. 2A, Table 1, Fig. S1). The GAM model has shown the highest AUC score (0.993), while CTA model has shown the lowest AUC score (0.946) and MAXENT could not qualify the AUC threshold (Table 1). Furthermore, the model identified that the Precipitation of Driest Quarter (Bio_17) made the most significant contribution, accounting for 32.61 % of the model's prediction, followed by Euclidean Distance from Water (water_1) (17.46 %), Elevation (ele_ba) (10.29 %), etc., while Aspect (aspect_ba) has the lowest contribution of 1.27 %. (Table 2, Figs. S2–S8). Out of the total distribution extent (1,42,000 km^2), about 9366 km^2 (6.59 %) is most suitable for the studied species, *L. cinerascens* (Fig. 2B).

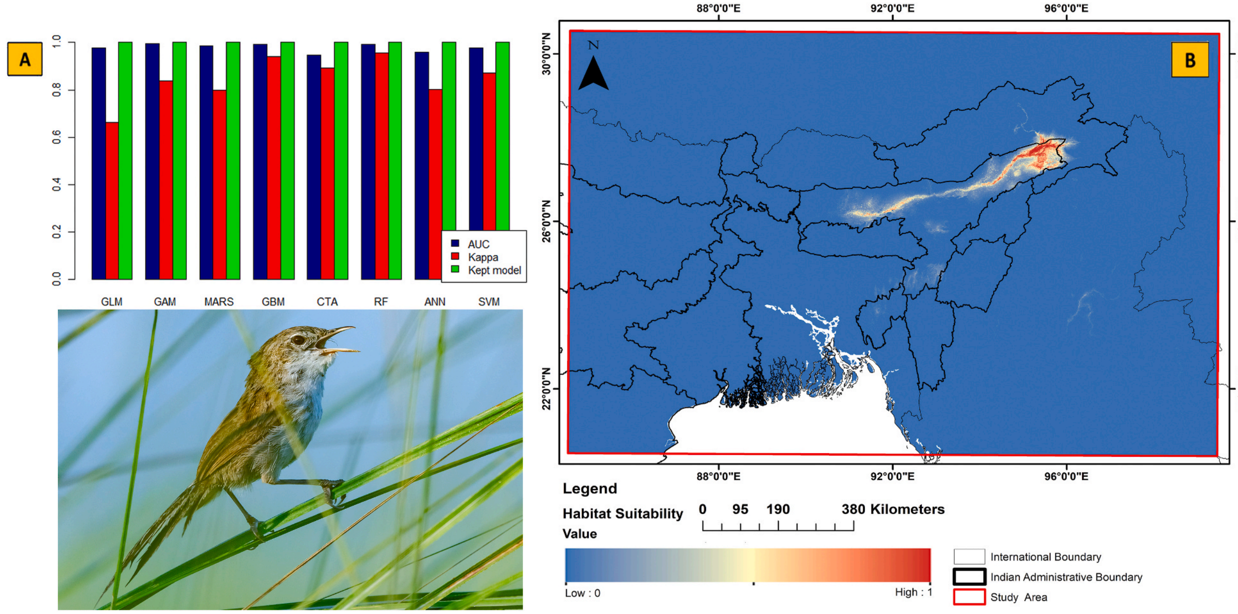

Fig. 2. (A) Bar Graph showing the performance of the selected models after model evaluation with AUC (>0.75), (B) Representing the suitable habitat for *L. cinerascens*. Photo Credit: Mr. Dhritiman Mukherjee.

Table 1
Model fit metrics for each of the participating modelling methods and for the final ensemble model for estimation of habitat suitability of Swamp Grass-babbler. Total Eight model algorithms were found to be selected with a threshold of <0.75 AUC score, i.e., Generalized linear model (GLM), Multivariate adaptive regression splines (MARS), Artificial Neural Network (ANN), Support Vector Machine (SVM), Random forests (RF), Classification Tree Analysis (CTA), and Gradient Boosting Machine (GBM).

Models	AUC	Sensitivity	Specificity	PCC	Kappa
GLM	0.977775	0.923529	0.920333	0.920659	0.663375
GAM	0.993912	0.961765	0.967000	0.966467	0.837735
MARS	0.985108	0.955882	0.957333	0.957186	0.799219
GBM	0.991609	0.964706	0.976471	0.970588	0.941176
CTA	0.946843	0.944118	0.947059	0.945588	0.891176
RF	0.991349	0.979412	0.976471	0.977941	0.955882
ANN	0.958607	0.947059	0.855882	0.901471	0.802941
SVN	0.978114	0.935294	0.935294	0.935294	0.870588
Ensemble	0.977915	0.951471	0.941980	0.946899	0.845262

The comparative analysis between current and future models indicates a substantial decrease in suitable habitat for *L. cinerascens* in future scenarios. Specifically, between 2041 and 2060, the decline is projected to be approximately 10.93 % for ssp126, 94.65 % for ssp245, and 93.61 % for ssp585, compared to the present distribution. Furthermore, for the period between 2061 and 2080, the results suggest a decrease of 33.53 % for ssp126, 95.02 % for ssp245, and 98.82 % for ssp585. In the current scenario, the area with the most suitable habitats for *L. cinerascens* measures 9366 km^2 (Fig. 2B). However, in the future climate scenarios by the year 2060, this habitat may decrease to 8393 km^2, 502 km^2, and 599 km^2 for ssp126, ssp245, and ssp585, respectively. These habitat areas could further reduce to 6226 km^2, 467 km^2, and 111 km^2 by the year 2080 (Fig. 3A–F).

3.2. Habitat quality, geometry and complexity

In the current scenario, higher values of Landscape Patch Index (LPI) (0.0373) and Aggregation Index (AI) (81.821) indicate the presence of larger patches in close proximity, along with lower values of Total Edge (TE) (57.024), Edge Density (ED) (4375.983), and Landscape Shape Index (LSI) (18.371), suggesting that the patches have simpler shape geometry (Table 3).

In the future projected scenario under SSP126 for the time frames 2041–2060 and 2061–2080, there is a significant increase in NP, with increase of 343.47 % and 292.174 %, respectively, indicating a fragmentation of suitable habitats. Moreover, diminished values of LPI by 71.38 % and 83.92 %, and AI by 36.95 % and 44.49 %, suggesting a reduction of patch sizes and increased dispersion (Table 3). Additionally, higher values of TE, ED, and LSI signify that the patches exhibit more edges and greater complexity, reflecting intensified fragmentation. Conversely, under the SSP245 climate change scenario, NP decreased by 35.07 % (2041–2060) and 36.52 % (2061–2080), respectively. Furthermore, the reduction in NP corresponded to a decrease in LPI (98.92 % and 99.03 %) and AI (66.86 % and 66.35 %) during the time periods of 2041–2060 and 2061–2080, respectively.

Moreover, this trend is further escalated in both time spans (2041–2060 and 2061–2080) within the SSP585 scenario. There has been a substantial decrease in NP, with a decline ranging from 14.78 % to 74.78 % in both periods, attributable to significant habitat loss. Consequently, there has been a corresponding decrease in LPI (98.84 % and 99.86 %) and AI (68.94 % and 85.33 %) in both timeframes (Table 3). Overall, these findings suggest a diminished number of patches that are more fragmented and dispersed from each other. However, the lower LSI value compared to the present scenario implies a simpler geometric shape due to the significant reduction in the total suitable area of the studied species.

3.3. PAs for conservation in present and future climate change scenarios

In the current context, DSNP in Assam has the highest habitat suitability for the studied species, with the mean suitability value of 0.822. Furthermore, among the assessed PAs in the species extent, such as Nameri National Park (NNP), Manas National Park (MNP), and Sonai-Rupai Wildlife Sanctuary (SRWLS), exhibit notably lower habitat suitability with values of 0.0607, 0.0196, 0.0056, and

Table 2
Percentage Contribution of Covariates selected for the ensemble model run.

Variable Abbreviations	Variables	Percentage Contribution (%)
bio_17	Precipitation of Driest Quarter	32.61
water_1	Euclidian Distance from Major Waterbodies	17.46
ele_ba	Elevation	10.29
bio_15	Precipitation Seasonality (Coefficient of Variation)	10.02
bio_1	Annual Mean Temperature	8.32
lulc_b	Land Use and Land Cover	7.91
bio_18	Precipitation of Warmest Quarter	5.95
bio_8	Mean Temperature of Wettest Quarter	4.11
built_up	Built Up	2.06
aspect_ba	Aspect	1.27

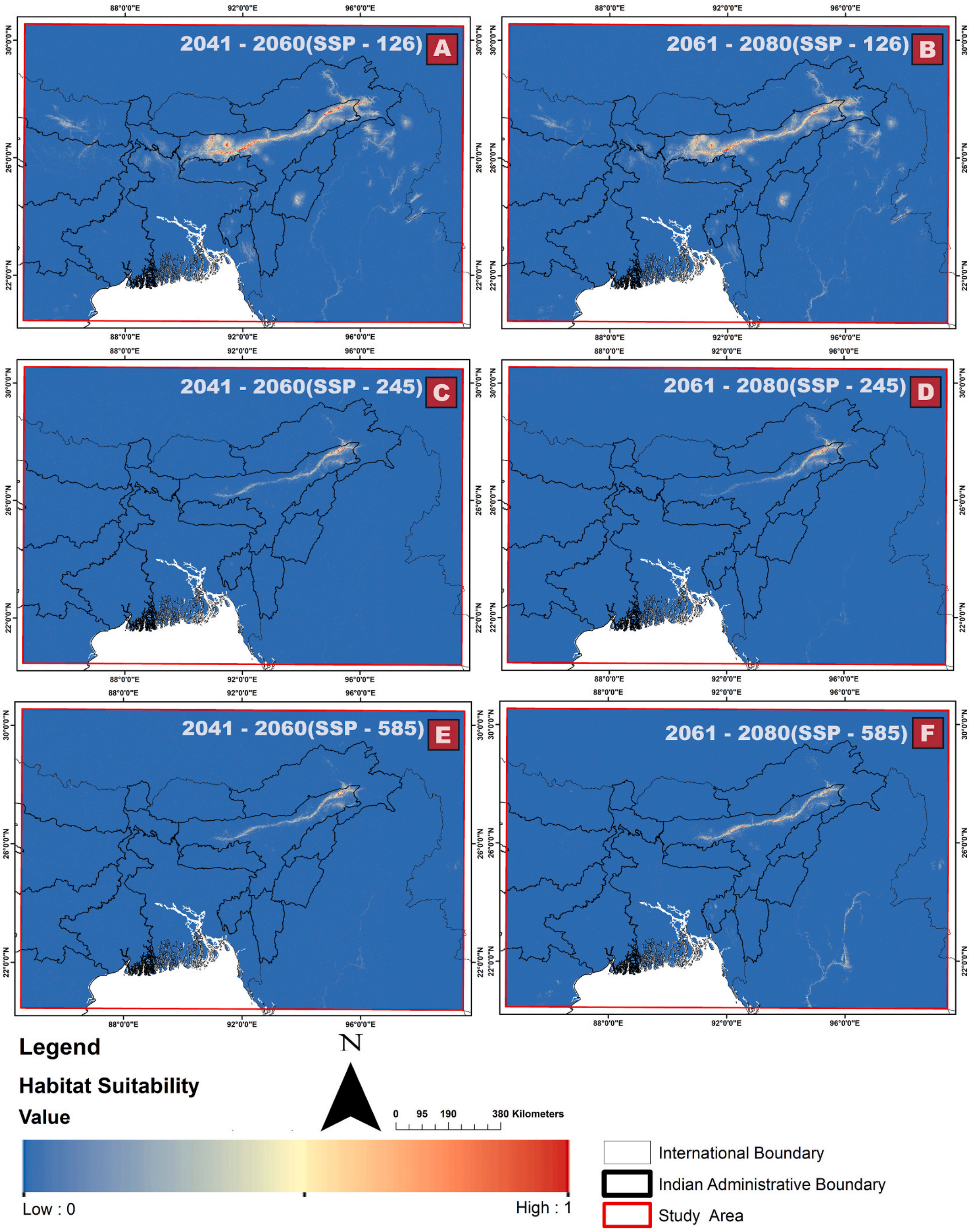

Fig. 3. The habitat suitability for *L. cinerascens* in future climatic projection scenarios of ssp126, ssp245 and ssp585 future scenarios for the year 2041–2060 and 2061–2080. (A) The projection for the years 2041–2060-SSP-126, (B) the year 2061–2080-SSP-126, (C) years 2041–2060-SSP-245, and (D) years 2061–2080-SSP-245, (E) years 2041–2060-SSP-585, (F) years 2061–2080-SSP-585. All the maps were prepared using ArcGIS 10.6 in the present study.

0.0015, respectively. Moreover, the findings of the study also revealed that DMWLS (0.660) is the only PA in Arunachal Pradesh that was found to have high habitat suitability for *L. cinerascens*. Interestingly, only Assam and Arunachal Pradesh demonstrated suitability for this species in the current scenario, while no other states within its historical extent exhibited such suitability.

The future projection under SSP 126 indicates a significant decline in the mean habitat suitability throughout the PAs. The most significant reduction occurs in DSNP, with a staggering 94.5 % reduction between 2041 and 2060. Additionally, there were serious declines in other PAs during this period, including PDWLS (88.98 %), ONP (80.89 %), BWLS (71.63 %), and KNP (77.75 %). Interestingly, DMWLS in Arunachal Pradesh remains relatively stable, with no substantial change in mean habitat suitability. However, the

Table 3
Habitat quality assessment of *Laticilla cinerascens* in distribution range for present and future climatic scenarios.

Climatic Scenarios	NP	PD	LPI	TE	ED	LSI	AI
Present	345	2647506	0.3732	57.0240	4375.9830	18.3711	81.8211
SSP 126 (2041–2060)	1530	11766583	0.1068	130.7680	10056.8100	44.6612	51.5846
SSP 126 (2061–2080)	1353	10405351	0.0600	109.8960	8451.6370	43.4747	45.4124
SSP 245 (2041–2060)	224	1722689	0.0040	11.9040	915.4863	16.5333	27.1116
SSP 245 (2061–2080)	219	1684236	0.0036	11.0240	847.8093	15.6591	27.5281
SSP 585 (2041–2060)	294	2261030	0.0043	14.4960	1114.8260	18.4898	25.4134
SSP 585 (2061–2080)	87	669080.2	0.0005	3.1680	243.6375	9.0000	12.0000

decrease intensifies further between 2061 and 2080, with DSNP (96.39 %) and DMWLS (95.17 %) in contrast to the present situation. Moreover, in the future climate change projections (SSP245 and SSP585) for the years 2041–2060 and 2061–2080, an enormous decline (>99 %) in mean habitat suitability is further detected in all PAs within the distribution range (Table 4)

3.4. *Connectivity and shape complexity among the PAs*

The analysis of connectivity between PAs on the northern and southern banks of the Brahmaputra River demonstrates significant variation in projected pathways across different time periods (Table 5, Fig. 4). The corridor connection between the five PAs on the southern bank of the Brahmaputra River was determined to be the highest between KNP and PDWLS, with a mean connectivity value of 13.158051, and the lowest between KNP and LWLS/BWLS (11.688092). Noticeably, the two PAs located on the northern bank, offering suitable habitat for the studied species, namely ONP and DMWLS, however exhibited the lowest mean connectivity of 7.787188, which may attribute to the significant distance and scarcity of suitable refuges between them. Most interestingly, two PAs (DSNP and DMWLS) situated in two opposite riverbanks shows significantly high mean connectivity of 13.069613.

In future climate change scenarios (SSP126, SSP245, and SSP585), there is an overall decrease in connectivity ranging from 5 % to 16 % among the southern bank PAs in both timeframes, except for DSNP and PDWLS, where connectivity has increased over 3 % (Fig. 5A–F). Among the southern bank PAs, the connectivity notably declines between KNP and PDWLS (>12 % in the 2041–2060 timeframe under the SSP126 scenario) and between KNP and LWLS/BWLS (>12 % in the 2041–2060 timeframe under the SSP126 scenario). Similarly, the connectivity between the two PAs situated on the northern bank experiences decline of 7 %–10 % in all climate change projections. Interestingly, connectivity between DSNP (southern bank) and DMWLS (northern bank) increases in all future climate change scenarios, with an increase exceeding 13 % in the 2041–2060 timeframe for both the SSP245 and SSP585 scenarios. The evaluation of connectivity fragmentation (Table 6) unveiled an LSI measure of 10.3776 and a SPLIT value of 1732721.131. However, in the future projections under SSP126, SSP245, and SSP585 for the periods 2041–2060 and 2061–2080, the LSI has shown an increase (>34 %), while the SPLIT has escalated, ranging from 70 % to 220 % across all climatic scenarios.

4. Discussion

Over the past century, there has been a significant surge in the rates of species extinction, marking the onset of the planet's sixth mass extinction event, primarily driven by anthropogenic activities and climate change [76]. The escalation in temperatures has the potential to amplify these issues, leading to further declines in species populations, reductions in their geographic ranges, and spatiotemporal shifts in bird communities at the continental scale [6,44,77]. Therefore, safeguarding avian and other vertebrates' biodiversity has become a foremost objective aiming to support both ecosystems and human well-being, with a focus on research initiatives for lesser-known vulnerable species in order to facilitate effective conservation action strategies [55,78,79]. Hence, the present investigation concentrating on the endangered *L. cinerascens*, endemic to northeast India, is in line with the necessity of emphasizing conservation endeavors by identifying habitat suitability and fragmentation under different climatic scenarios.

The Swamp Grass-babbler was frequently observed in DSNP and served as the sole refuge for many years. However, in 2010, the species was last sighted in this PA as the grasslands on its periphery were entirely burned and cleared by local communities for agricultural purposes. This resulted in an extended absence of sightings of this species within the park or any other locations for about four years. Subsequently, in 2014, the species was recorded in DMWLS in Arunachal Pradesh and has continued to be observed since then. Possibly due to heightened awareness among local communities residing near DSNP, the grassland habitat gradually regenerated, leading to the species being sighted once again in 2019, marking its reappearance after nearly a decade of absence. Furthermore, in 2020, the species was spotted for the first time near the Brahmaputra Plains on the outskirts of Guwahati City, as documented on social media platforms. Therefore, the ecological study of these entire refuges has been critically important for the past decades.

The present study unveiled a significant reduction in suitable habitat for *L. cinerascens* in future climate scenarios, with a concerning decline ranging from 10 % to 94 % across both time periods in the selected SSPs (SSP126, SSP245, and SSP585).The decline witnessed by the study species corresponds to a parallel trend observed in another endangered species, White-winged Duck (*Asarcornis sculuta*), inhabiting in the same distribution range [54]. Moreover, the outcomes delve into the fragmentation of habitats, shedding light on the interplay between climate change and habitat fragmentation. The analysis of habitat fragmentation unveiled the disintegration of suitable habitats in future scenarios, resulting in an increase in patchiness characterized by expanded edge areas and a reduced size of suitable habitats. These fragmented areas are spatially distant from each other and exhibit simpler geometric shapes. However, an increase in the NP was observed in the SSP126 scenario, which prioritizes reduced greenhouse gas emissions and

Table 4

Representing the mean suitability of PAs in the present and future SSP scenarios. AS: Assam, AR: Arunachal Pradesh, DSNP: Dibru Saikhowa National Park, DMWLS: D'Ering Memorial Wildlife Sanctuary, ONP: Orang National Park, BWLS: Burachapori Wildlife Sanctuary, PDWLS: Pani – Dihing Wildlife Sanctuary, KNP: Kaziranga National Park, LWLS: Laokhuwa Wildlife Sanctuary; NNP: Nameri National Park, MNP: Manas National Park, SRWLS: Sonai – Rupai Wildlife Sanctuary. The percentage (%) change represents the change in mean habitat suitability from the present senario. The decline is denoted by "−".

Sl. No.	Protected Areas & State	Present	SSP 126		SSP 126		SSP 245		SSP 245		SSP 585		SSP 585	
			(2041–2060)		(2061–2080)		(2041–2060)		(2061–2080)		(2041–2060)		(2061–2080)	
		Mean	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)
1	DSNP (AS)	0.822777	0.045236	−94.50	0.029651	−96.39	0.005936	−99.27	0.003644	−99.55	0.002842	−99.65	0.000545	−99.93
2	DMWLS (AR)	0.660516	0.660516	0	0.031859	−95.17	0.005074	−99.23	0.003669	−99.44	0.002399	−99.63	0.000451	−99.93
3	ONP (AS)	0.312481	0.059688	−80.89	0.042226	−86.48	0.002407	−99.22	0.001011	−99.67	0.001415	−99.54	0.000565	−99.81
4	BWLS (AS)	0.164159	0.046561	−71.63	0.036391	−77.83	0.001655	−98.99	0.000754	−99.54	0.001032	−99.37	0.000397	−99.75
5	PDWLS(AS)	0.158438	0.017458	−88.98	0.012801	−91.92	0.001401	−99.11	0.001011	−99.36	0.000660	−99.58	0.000155	−99.90
6	KNP (AS)	0.118197	0.026297	−77.75	0.020279	−82.84	0.001336	−98.87	0.000846	−99.28	0.000766	−99.35	0.000276	−99.77
7	LWLS (AS)	0.060769	0.028406	−53.26	0.021512	−64.60	0.000844	−98.61	0.000412	−99.32	0.000516	−99.15	0.000208	−99.66
8	NNP (AS)	0.019657	0.012185	−38.01	0.009153	−53.44	0.000245	−98.75	0.000190	−99.03	0.000148	−99.25	0.000057	−99.71
9	MNP (AS)	0.005636	0.010302	82.79	0.008518	51.14	0.000039	−99.31	0.000059	−98.95	0.000022	−99.61	0.000007	−99.88
10	SRWLS (AS)	0.001598	0.001052	−34.17	0.000764	−52.19	0.000016	−99	0.000013	−99.19	0.000010	−99.37	0.000003	−99.81

Table 5

Representing the mean suitable connectivity between PAs in the present and future SSP scenarios. DSNP: Dibru Saikhowa National Park, DMWLS: D'Ering Memorial Wildlife Sanctuary, ONP: Orang National Park, BWLS: Burachapori Wildlife Sanctuary, PDWLS: Pani – Dihing Wildlife Sanctuary, KNP: Kaziranga National Park, LWLS: Laokhuwa Wildlife Sanctuary; NNP: Nameri National Park, MNP: Manas National Park, SRWLS: Sonai – Rupai Wildlife Sanctuary. The percentage (%) change represents the change in mean connectivity from the present senario. The decline is denoted by "−".

Connectivity (Current flow) between PAs	Present	SSP 126 (2041–2060)		SSP 126 (2061–2080)		SSP 245 (2041–2060)		SSP 245 (2061–2080)		SSP 585 (2041–2060)		SSP 585 (2061–2080)	
	Mean	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)	Mean	(%)
DSNP_DMWLS	13.069613	13.934976	6.62	13.865217	6.09	14.789700	13.16	14.552322	11.34	14.821599	13.41	14.505506	10.99
DSNP_PDWLS	12.105204	12.722217	5.10	12.570313	3.84	13.354200	10.32	13.326741	10.09	13.317761	10.02	13.122426	8.40
KNP_PDWLS	13.158051	11.478123	−12.77	11.490200	−12.68	13.053863	−0.79	12.628702	−4.02	13.029981	−0.97	13.267280	0.83
KNP_LWLS_BWLS	11.688092	9.816178	−16.02	9.838748	−15.82	11.157775	−4.54	10.500233	−10.16	11.247324	−3.77	11.585956	−0.87
ONP_LWLS_BWLS	10.780844	8.615338	−20.09	8.610298	−20.13	9.904215	−8.13	9.355058	−13.23	9.871793	−8.43	10.274437	−4.70
ONP_DMWLS	7.787188	7.167877	−7.95	7.075877	−9.13	7.125436	−8.49	6.995436	−10.16	7.051812	−9.44	7.032817	−9.68

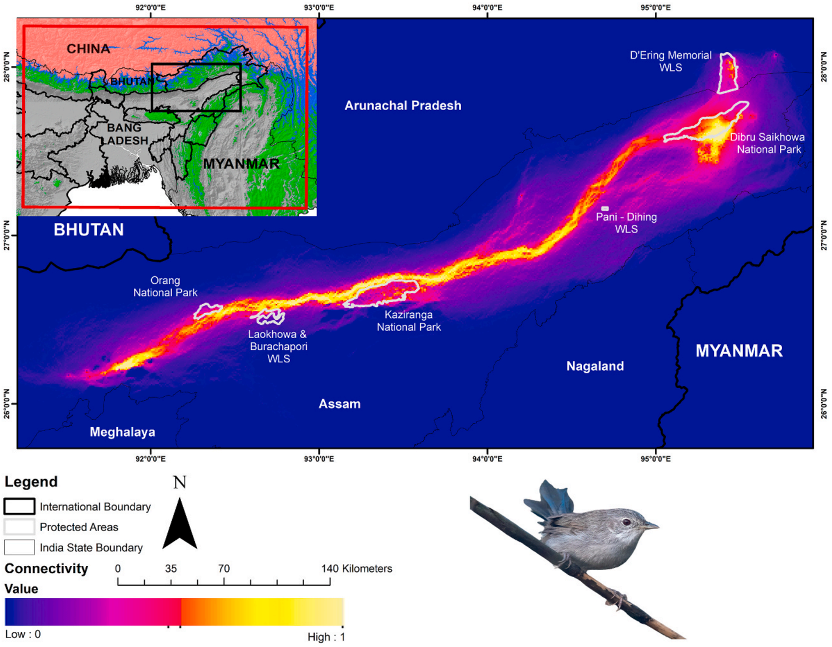

Fig. 4. Map representing the habitat connectivity between the PAs for Swamp Grass-babbler *L. cinerascens* in North Eastern India in present scenario. Photo Credit: Mr. Rofikul Islam.

sustainable development practices. As a result of these sustainable practices, the decline in suitable areas was much lesser (10 %–30 %) compared to other scenarios (SSP245 and SSP585) where the decline exceeded 90 % from the present. Therefore, with a reduction in suitable area exceeding 90 % in SSP245 and SSP585, the NP decreased as patches began to disappear in these scenarios. Additionally, the observed high level of fragmentation in the SSP126 scenario denotes the onset of habitat fragmentation due to climate change. Moreover, considering the species' preference in grassland habitats adjacent to rivers, the heightened habitat fragmentation might be attributed to changes in land use and land cover patterns induced by climate change, as well as alterations in the course of the Brahmaputra River leading to floods and other natural disasters [80,81]. Conversely, the SSP245 and SSP585 scenarios experienced significant habitat loss, resulting in a substantial decrease in patch numbers, with the remaining patches being notably smaller in size and widely dispersed, akin to isolated islands. The findings also demonstrated that DMWLS is the only PA with suitable habitat in Arunachal Pradesh, and DSNP exhibits the highest habitat suitability among the other PAs in Assam. The observed habitat suitability and earlier sightings for this species are congruent with each other.

However, the current refuges demonstrate a significant decrease in habitat suitability in the future climate change scenarios (SSP126, SS245, and SSP585) in both time periods, with a notable decrease from 94 % to 99 % in DSNP. Interestingly, DMWLS plummeted the habitat suitability from 96 % to 99 % in other time periods but not affected in the SSP126 (2041–2061) scenario. Therefore, there is an urgent need protection for the PAs that are prone to being suitable habitat for the study species. It is additionally noteworthy that while PDWLS and LWLS provide suitable habitats, the species has not yet been sighted within the PAs. This incongruity could stem from potential missed or omitted sightings, yet it does not inherently signify the absence of the species in these regions.

Additionally, two south bank PAs (DSNP and PDWLS) demonstrated substantial habitat connectivity across various future projections. However, the remaining PAs located on both the south and north banks experienced notable declines, indicating a concerning situation for this species. Remarkably, there has been a rise in connectivity between two opposing riverbank PAs (DSNP and DMWLS). This observation is noteworthy as it contrasts with the established understanding that the Brahmaputra River has served as an ecological barrier for numerous other vertebrate species in previous periods [82–84]. The heightened connectivity between DSNP and DMWLS may be attributed to their close geographic location and the convergence of three major tributaries (Siang, Dibang, and Lohit) of the Brahmaputra River. At this juncture, the width of the tributaries is comparatively narrow, with numerous small and seasonal river channels dividing them. As a result, several sedimented islands with grassland ecosystems occasionally form between these channels, fostering increased proximity between the two river banks and potentially enhancing observed habitat connectivity. Eventually, leveraging the visualized connectivity among refuges, these observed corridors may play a pivotal role in enhancing conservation planning for this threatened species as suggested earlier [85,86]. The comprehensive analysis of habitat quality, connectivity, and landscape fragmentation across the species extent in Assam and Arunachal Pradesh unveils a complex and alarming scenario for this endangered species. The overall findings of this study paint a concerning picture for the current and future ecological outlook of *L. cinerascens*, emphasizing the urgent necessity for conservation efforts in both permanently and seasonally formed grassland habitats.

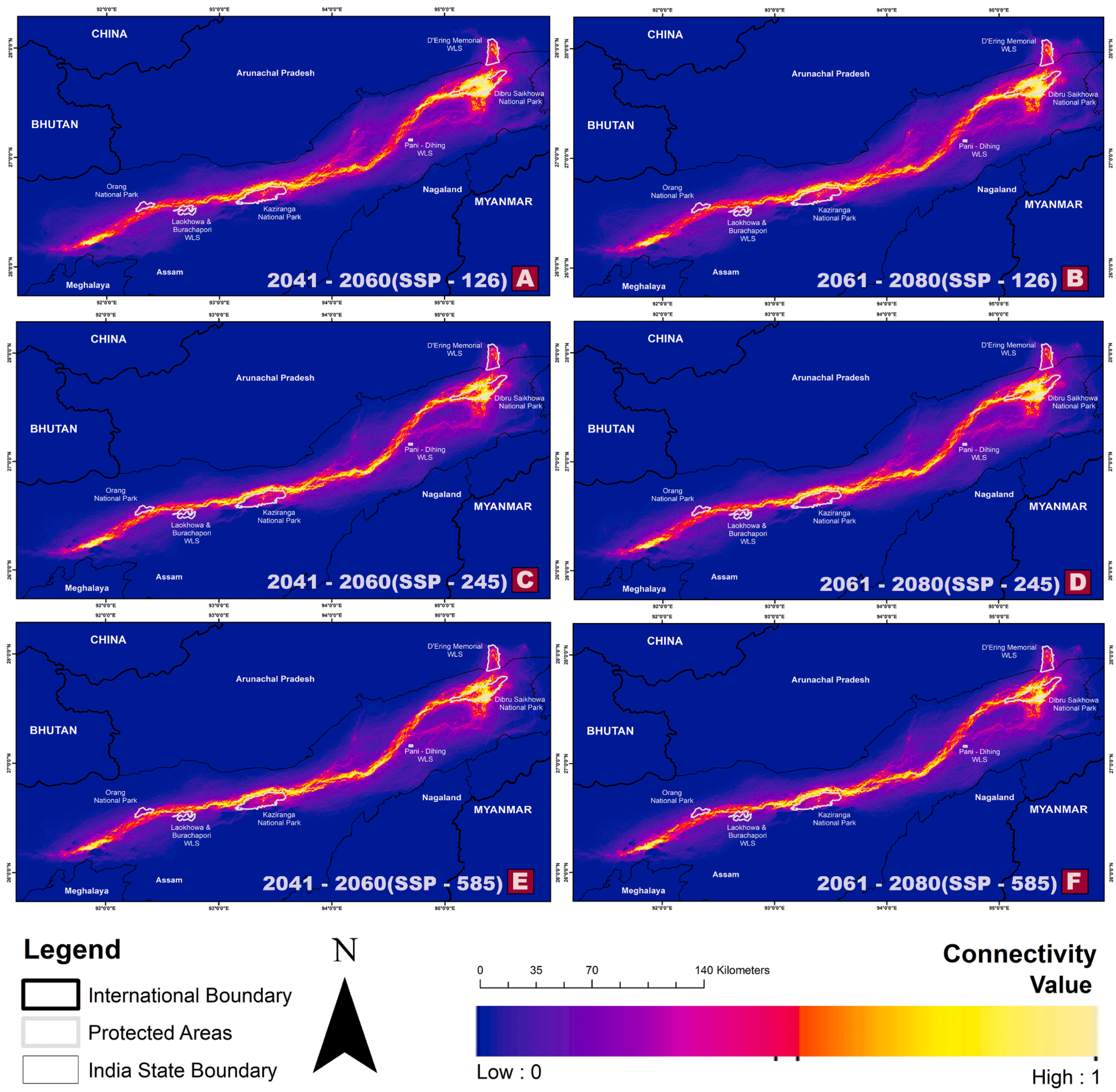

Fig. 5. Map representing the habitat connectivity between the PAs for Swamp Grassbabbler *L. cinerascens* in North Eastern India in future scenario. (A) The projection for the years 2041–2060-SSP-126, (B) the year 2061–2080-SSP-126, (C) years 2041–2060-SSP-245, and (D) years 2061–2080-SSP-245, (E) years 2041–2060-SSP-585, (F) years 2061–2080-SSP-585.

Table 6

Representing the shape complexity and geometry of connectivity between PAs in the present and future SSP scenarios.

Pathways	LSI	SPLIT
Present	10.3776	1732721.131
SSP 126 (2041–2060)	14.0000	3440926.473
SSP 126 (2061–2080)	14.1837	3170747.083
SSP 245 (2041–2060)	14.5000	3497935.662
SSP 245 (2061–2080)	14.3579	4724567.501
SSP 585 (2041–2060)	14.1368	2964259.852
SSP 585 (2061–2080)	14.7363	5561873.595

5. Conclusion

The ecological study of the Swamp Grass-babbler has historically endured from a lack of attention owing to its elusive nature, resulting in a limited understanding of its conservation requirements. Furthermore, the grasslands of northeast India, where these birds primarily reside, have experienced significant degradation in recent years due to various factors including alterations in river courses, flash floods, agricultural expansion, and climate fluctuations. Consequently, the ongoing threats faced by this endangered species demands prompt and thorough ecological assessments to prevent its extinction in the wild. This study reveals alarming trends of habitat degradation and fragmentation, intensifying the imminent risk for this species. In light of these findings, conservation endeavors must prioritize the preservation and restoration of habitats, with a focus on mitigating the adverse effects of climate change and addressing the underlying causes of habitat destruction. Moreover, it is crucial to undertake extensive surveys in Northeast India, with a specific focus on the grassland habitats of the Siang, Dibang, Subansiri, and Lohit River valleys, alongside areas beyond designated protected zones, to assess the feasibility of translocation and the initiation of breeding programs for the Swamp Grass-babbler. Moreover, it is essential to establish long-term monitoring and research programs to better understand how this species, as well as other grassland inhabitants, respond to habitat alterations, and to protect populations that currently lack adequate conservation measures. Conclusively, collaborative endeavors engaging local communities, policymakers, and conservation organizations are imperative for safeguarding the endangered Swamp Grass-babbler and its delicate ecosystem from the escalating threats it confronts.

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Data availability statement

Data used for the analysis were sourced from open-access resources. The records of field survey occurrences used for the model can be made available upon request.

CRediT authorship contribution statement

Imon Abedin: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Tanoy Mukherjee:** Writing – original draft, Visualization, Supervision, Software, Project administration, Investigation, Formal analysis, Conceptualization. **Hye-Eun Kang:** Visualization, Methodology, Formal analysis, Data curation. **Tae-Ho Yoon:** Visualization, Software, Methodology, Investigation, Data curation. **Hyun-Woo Kim:** Writing – review & editing, Validation, Resources, Investigation, Funding acquisition. **Shantanu Kundu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e30273.

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