

**STUDY ON THE DISTRIBUTION AND HABITAT
REQUIREMENTS OF THREE SELECT THREATENED
GRASSLAND BIRDS ALONG BRAHMAPUTRA RIVER OF
ARUNACHAL PRADESH AND ASSAM**

**Thesis submitted to Bharathiar University in partial fulfilment
of the requirements for the award of the degree of
DOCTOR OF PHILOSOPHY IN ZOOLOGY**

**Submitted by
HARIF P**

**Under the Guidance and Supervision of
Dr. ARUN, P. R.
Senior Principal Scientist**



**Sálim Ali Centre for Ornithology and Natural History (SACON)
South India Centre of Wildlife Institute of India
Ministry of Environment, Forest & Climate Change, Government of India
(Affiliated to Bharathiar University)
COIMBATORE – 641 046
TAMILNADU, INDIA**

SEPTEMBER 2025

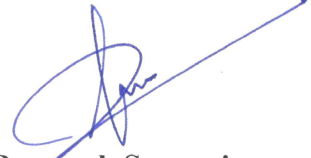
Certificate

CERTIFICATE

This is to certify that the thesis entitled “**STUDY ON THE DISTRIBUTION AND HABITAT REQUIREMENTS OF THREE SELECT THREATENED GRASSLAND BIRDS ALONG BRAHMAPUTRA RIVER OF ARUNACHAL PRADESH AND ASSAM**” submitted to the Bharathiar University, in partial fulfillment of the requirements for the award of the Degree of **DOCTOR OF PHILOSOPHY IN ZOOLOGY** is a record of original work done by **HARIF P** during the period of October 2018 to September 2025 of his study in the Department of Zoology at Sálím Ali Centre for Ornithology and Natural History (SACON) under my supervision and guidance, and the thesis has not formed the basis for the award of any Degree / Diploma / Associateship / Fellowship or other similar title to any candidate in any University.

Place: Anaikatty

Date: 24-09-2025



Research Supervisor

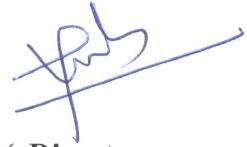
डॉ. पी. आर. अरुण / Dr. P. R. Arun
वरिष्ठ प्रधान वैज्ञानिक / Senior Principal Scientist
सालिम अली पक्षिविज्ञान एवं प्रकृति विज्ञान केन्द्र
Sulim Ali Centre for Ornithology and Natural History
आनैकट्टी, कोयम्बतूर - 641 108
Anaikatty (Post), Coimbatore - 641 108

Countersigned



Head of the Department

डॉ. पी. आर. अरुण / Dr. P. R. Arun
वरिष्ठ प्रधान वैज्ञानिक / Senior Principal Scientist
सालिम अली पक्षिविज्ञान एवं प्रकृति विज्ञान केन्द्र
Sulim Ali Centre for Ornithology and Natural History
आनैकट्टी, कोयम्बतूर - 641 108
Anaikatty (Post), Coimbatore - 641 108



Director

निदेशक / Director
भारतीय वन्यजीव संस्थान
Wildlife Institute of India
देहरादून / Dehradun

Declaration

DECLARATION

I, **HARIF P** hereby declare that the thesis entitled “**STUDY ON THE DISTRIBUTION AND HABITAT REQUIREMENTS OF THREE SELECT THREATENED GRASSLAND BIRDS ALONG BRAHMAPUTRA RIVER OF ARUNACHAL PRADESH AND ASSAM**” submitted to the Bharathiar University, in partial fulfilment of the requirements for the award of the Degree of **DOCTOR OF PHILOSOPHY IN ZOOLOGY** is a record of original and independent research work done by me during the period of October 2018 to September 2025 under the guidance and supervision of **Dr. P.R. ARUN**, Senior Principal Scientist at Sálím Ali Centre for Ornithology and Natural History (SACON), Department of Zoology and it has not formed the basis for the award of any other Degree / Diploma / Associateship / Fellowship or other similar titles to any candidate of any University.

Place: Anaikatty

Date: 24/09/2025



Signature of the Candidate

Countersigned



Research Supervisor

डॉ. पी. आर. अरुन / Dr. P.R. Arun
वरिष्ठ प्रधान वैज्ञानिक / Senior Principal Scientist
सालिम अली पक्षिविज्ञान एवं प्रकृति विज्ञान केन्द्र
Sálím Ali Centre for Ornithology and Natural History
आनैकट्टी, कोयंबटूर - 641 108
Anaikatty (Post), Coimbatore - 641 108

*Certificate of Genuineness of
Publication*

CERTIFICATE OF GENUINENESS OF THE PUBLICATION

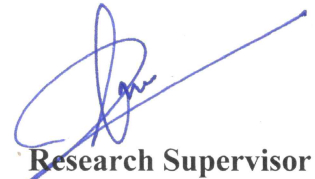
This is to certify that the Ph.D. candidate **Mr. Harif P** working under my supervision has published research articles in standard refereed/SCI journals as listed below:

1. Parengal, Harif., PR, Arun., Dutta, Sarbasis., & Joy, Anisha. (2025). Distribution, habitat shift, and conservation needs of Jerdons Babbler (*Chrysomma altirostre*): A study of a vulnerable grassland specialist. *Ornis Hungarica*, 33(2): 224–237.
2. Parengal, Harif., PR, Arun., MR, Sethu., P, Haris., GC, Bency., & P, Sumayyabi. (2025). Tropical Riverine Grasslands of the Brahmaputra Basin: A Critical Assessment of Biodiversity Threats, Conservation Challenges, and Management Imperatives. *International Journal of Plant and Environment*, 11.
3. Parengal, Harif., P. R, Arun., & Salim, A. (2025). Distribution patterns of the Marsh Babbler (*Pellorneum palustre*) in Brahmaputra grasslands: An integrated citizen science approach. *Tropical Conservation Ecology*, 1, 11–24.
4. Prabhakaran, Sandeep., Sharief, M. U., Parengal, Harif., Karunakaran, P. V., Kumara, H. N., & Babu, S. (2024). The Relationship between Landscape Metrics and Human Interventions on the Floristic Structure and Composition of the Community Reserves of Meghalaya, India. *International Journal of Plant and Environment*, 10(04), 73–83.
5. Kumara, H. N., Babu, S., Rao, G. B., Mahato, S., Bhattacharya, M., Rao, N. V. R., Tamiliniyan, D., Parengal, Harif., Deepak, D., Balakrishnan, A., & Bilaskar, M. (2022). Responses of birds and mammals to long-established wind farms in India. *Scientific Reports*, 12(1), 1339.

The contents of the above publications have been incorporated as part of the results presented in his thesis.

Place: **Anaikatty**

Date: **24-09-2025**


Research Supervisor

डॉ. पी. आर. अरुन / Dr. P. R. Arun
वरिष्ठ प्रधान वैज्ञानिक / Senior Principal Scientist
सालिम अली पक्षिविज्ञान एवं प्रकृति विज्ञान केन्द्र
Salim Ali Centre for Ornithology and Natural History
आनैकट्टी, कोयंबटूर - 641 108
Anaikatty (Post), Coimbatore - 641 108

Countersigned


Head of the Department

डॉ. पी. आर. अरुन / Dr. P. R. Arun
वरिष्ठ प्रधान वैज्ञानिक / Senior Principal Scientist
सालिम अली पक्षिविज्ञान एवं प्रकृति विज्ञान केन्द्र
Salim Ali Centre for Ornithology and Natural History
आनैकट्टी, कोयंबटूर - 641 108
Anaikatty (Post), Coimbatore - 641 108


Director
निदेशक / Director
भारतीय वन्यजीव संस्थान
Wildlife Institute of India
देहरादून / Dehradun

Certificate of Plagiarism Check



பாரதியார் பல்கலைக்கழகம்

BHARATHIAR UNIVERSITY

COIMBATORE - 641 046, TAMILNADU, INDIA

| State University | Accredited With A++ Grade - 3.63 CGPA by NAAC | 15th Rank among Indian Universities by MoE-NIRF |

CERTIFICATE OF PLAGIARISM CHECK

1	Name of the Research Scholar	HARIF P
2	Course of study	M.Phil., / Ph.D.,
3	Title of the Thesis / Dissertation	Study on the distribution and habitat requirements of three select threatened grassland birds along Brahmaputra River of Arunachal Pradesh and Assam.
4	Name of the Supervisor	Dr. Arun, P. R.
5	Department / Institution/ Research Centre	Salim Ali Centre for Ornithology and Natural History, South India, Centre of Wildlife Institute of India. ZOOLOGY
6	% of Similarity of content Identified	01 %
7	Acceptable Maximum Limit	10 %
8	Software Use	Drillbit
9	Date of verification	17/09/2025

Report on plagiarism check, items with % of similarity is attached


Signature of the Supervisor

(Seal)
டீ. பி. அரூன் / Dr. P. R. Arun
வரிசுத ப்ரதான வேதானிக / Senior Principal Scientist
சாலிம் அலி பசிவிஜ்னான் எவ் ப்ரக்தி விஜ்னான் கெந்
Sálim Ali Centre for Ornithology and Natural History
அனேகட்டி, கோயம்புத்தூர் - 641 108
Anaikatty (Post), Coimbatore - 641 108


Signature of the Researcher

Head of the Department
(Seal)

டீ. பி. ப்ரமோத / Dr. P. Pramod
வரிசுத ப்ரதான வேதானிக / Senior Principal Scientist
சாலிம் அலி பசிவிஜ்னான் எவ் ப்ரக்தி விஜ்னான் கெந்
Sálim Ali Centre for Ornithology and Natural History
அனேகட்டி, கோயம்புத்தூர் / Anaikatty, Coimbatore - 641 108


University Librarian (BU)
University Librarian
Arignar Anna Central Library
Bharathiar University
Coimbatore - 641 046.

Director i/c
Center for Research & Evaluation (BU)
(Seal)



Bharathiar University
Certificate of Plagiarism Check for Thesis

Author Name	Harif. P
Course of Study	Ph.D
Name of Guide	Dr. P.R. Arun
Department	Zoology
Acceptable Maximum Limit	10
Submitted By	buaacl.urkund@gmail.com
Paper Title	Study on the distribution and habitat requirements of three select threatened grassland birds along Brahmaputra River of Arunachal Pradesh and Assam
Similarity	1%
Paper ID	4371296
Total Pages	126
Submission Date	2025-09-17 10:28:34


University Librarian
Arignar Anna Central Library
Bharathiar University
Coimbatore - 641 046.

* This report has been generated by DrillBit Anti-Plagiarism Software

Acknowledgment

ACKNOWLEDGEMENT

I express my deepest gratitude to my research supervisor, Dr. P.R. Arun, Senior Principal Scientist, Environmental Impact Assessment Division, Sálim Ali Centre for Ornithology and Natural History (SACON), South India Centre for Wildlife Institute of India, for his guidance, invaluable insights, and encouragement throughout this research journey.

I am profoundly grateful to the scientific community at SACON for their continuous support and intellectual contributions. I sincerely thank the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, for funding the project “Assessing the distribution, population and habitat use of three endangered species to develop a conservation plan for species and their habitats.” I am deeply grateful to the Principal Investigator, Dr. S. Babu, Senior Scientist, SACON, and the Co-Investigators Dr. R. Jayapal, Senior Principal Scientist, SACON; Dr. Honnavalli N. Kumara, Principal Scientist, SACON; and Dr. M. Shirish, Principal Scientist, SACON, for their constant guidance, support, and valuable inputs throughout the study. I also extend my heartfelt thanks to all scientific, technical, and administrative staff members of SACON for their kind cooperation and support.

This research was enriched by the collaborative efforts and field assistance of dedicated co-researchers. I am deeply thankful to Nandu V.S., Ashwin C.P., Alby J. Mattathil, Sarbasis Dutta, Dr. Anoop Raj P.N., Angel Joy, Anjitha Devarajan, Sujin N.S., Krishnapriya, Ashiya, D. Tamiliniyan and Dr. S. Suresh Marimuthu for their tireless efforts during field surveys, data collection, and for their valuable insights that significantly contributed to this study.

I acknowledge with gratitude Dr. C. Gunasekaran, Assistant Professor, Department of Zoology, Bharathiar University, and Dr. P. Pramod, Senior Principal Scientist, SACON, for their constructive feedback on the Ph.D. research work and their continuous support throughout the research process. Their critical reviews and suggestions substantially improved the scientific rigor of this work.

Special acknowledgment goes to Dr. Mirium M. Abraham, Sandeep Prabhakaran, Sethu Mathavan, Dr. Anoop V. and Jeffrey Schwilk, from the Centre for Tropical

Biodiversity Conservation for providing access to their facilities for data analysis and other critical phases of this thesis. Their institutional support and the chairperson's permission to utilize their research infrastructure were invaluable to the successful completion of this study.

I am indebted to my family for their unwavering love, patience, and sacrifices throughout this academic journey. My profound gratitude goes to my parents, Kunhachumma Srambikkal and Hamza Parengal, and my brothers, Haris Parengal and Haneefa Parengal, for their constant encouragement and moral support. I extend my heartfelt appreciation to all extended family members whose belief in my capabilities provided strength during challenging times.

To my beloved wife, Jamal Rifana, I owe immeasurable gratitude for her patience, understanding, and unwavering support throughout this demanding research period. Her emotional support and encouragement were instrumental in maintaining my motivation. My children, Muhammed Azlan Parengal and Amna Parengal, have been my constant source of inspiration and joy.

I acknowledge my dear friends and colleagues who provided constant motivation, intellectual discussions, and moral support throughout this journey. Their companionship and encouragement have been invaluable in overcoming the challenges encountered during this research.

I am grateful to the forest departments of Assam and Arunachal Pradesh, and the management authorities of various protected areas for granting necessary permissions for field surveys. The cooperation of local communities in the study areas, whose traditional knowledge of grassland ecosystems enriched this research, is deeply appreciated.

Finally, I extend my gratitude to all individuals and institutions who, directly or indirectly, contributed to the successful completion of this research. This work represents not only personal academic achievement but also a contribution toward the conservation of India's threatened grassland avifauna, particularly in the ecologically sensitive Brahmaputra River system.

Harif P

Table of Contents

TABLE OF CONTENTS

1	Chapter 1	1
1.1	Background	1
1.1.1	Overview of grassland ecosystems in Northeast India	1
1.1.2	Importance of Brahmaputra floodplains	2
1.1.3	Introduction to target species	5
1.2	Research Gap and Significance	7
1.3	Research Objectives.....	8
1.4	Thesis Structure Overview.....	8
1.5	Study Area Description.....	9
1.5.1	Assam.....	11
1.5.2	Arunachal Pradesh	17
2	Chapter 2.....	23
2.1	Grassland Ecosystems of the Brahmaputra Valley	23
2.1.1	Ecosystem structure and dynamics	23
2.1.2	Vegetation communities	24
2.1.3	Soil processes and nutrient dynamics	24
2.1.4	Human impacts	25
2.1.5	Global comparisons	25
2.2	Ecology of Jerdon's Babbler	25
2.3	Ecology of Black-breasted Parrotbill.....	27
2.4	Ecology of Marsh Babbler	28

2.5	Habitat Requirements of Grassland Birds.....	28
2.5.1	Patch size and landscape context	30
2.5.2	Climate variables	31
2.5.3	Soil characteristics	31
2.5.4	Water availability and wetland proximity.....	32
2.6	Conservation Status and Threats.....	32
2.6.1	Global conservation status of grassland birds.....	33
2.6.2	Habitat loss and conversion	33
2.6.3	Agricultural intensification	34
2.6.4	Infrastructure development and fragmentation.....	34
2.6.5	Climate change.....	35
2.6.6	Invasive species	36
2.6.7	Fire regime alterations	36
2.6.8	Pollution and contamination	37
2.6.9	Traditional land use changes.....	37
2.6.10	Water resource development.....	37
2.7	Species Distribution Modelling in Avian Conservation	38
2.7.1	Ensemble modelling approaches.....	38
2.7.2	Machine learning techniques	38
2.7.3	Bioclimatic variables and remote sensing.....	39
3	Chapter 3.....	40
3.1	Introduction.....	40
3.1.1	Chapter objectives and structure.....	41
3.2	Methods.....	41
3.2.1	Data analysis framework.....	41

3.2.2	Variable selection and ecological justification	42
3.2.3	Data preprocessing and quality control.....	44
3.2.4	Correlation analysis and multicollinearity assessment	44
3.2.5	Principal component analysis	44
3.2.6	Generalized linear models.....	46
3.2.7	Random Forest Analysis	47
3.3	Results.....	47
3.3.1	Habitat characteristics and distribution patterns of Jerdon's Babbler	47
3.3.2	Habitat associations and environmental variables	47
3.3.3	Habitat characteristics and distribution patterns of Black-breasted Parrotbill (<i>Paradoxornis flavirostris</i>)	53
3.3.4	Habitat characteristics and distribution patterns of Marsh Babbler (<i>Pellorneum palustre</i>)	58
3.4	Discussion	63
3.4.1	Species-specific habitat requirements and ecological specialization.....	63
3.4.2	Spatial distribution patterns and conservation priorities.....	64
3.4.3	Conclusion	64
4	Chapter 4.....	66
4.1	Introduction.....	66
4.2	Methods.....	68
4.2.1	Anthropogenic pressure	68
4.2.2	Fire data collection and processing.....	68
4.2.3	Climatic threats	70
4.2.4	Documentation of other threats during field survey	70
4.3	Results.....	70
4.3.1	Anthropogenic threats	70

4.3.2	Indirect threats and cumulative impacts	74
4.4	Discussion	75
5	Chapter 5	78
5.1	Introduction	78
5.1.1	Advances in species distribution modelling	79
5.1.2	Climate change scenarios and future projections.....	80
5.1.3	Population recovery site identification	80
5.2	Methods.....	81
5.2.1	Study area.....	81
5.2.2	Data acquisition	81
5.2.3	Remote sensing and geographic information system analysis.....	82
5.2.4	Species distribution modelling framework	83
5.2.5	Environmental variable selection and climate data	84
5.2.6	Overlay analysis for population recovery site identification	85
5.2.7	Data processing and quality control.....	86
5.3	Results.....	87
5.3.1	Individual algorithm performance	87
5.3.2	Ensemble modelling outcomes	88
5.3.3	Current and future potential habitats of Jerdon’s Babbler	88
5.3.4	Current and future potential habitats of Black-breasted Parrotbill	95
5.3.5	Current and future potential habitats of Marsh Babbler	99
5.3.6	Climate refugia.....	105
5.4	Discussion	108
5.4.1	Algorithm performance and methodological implications	108
5.4.2	Environmental drivers of species distribution	108

5.4.3	Magnitude and patterns of climate-induced habitat loss.....	109
5.4.4	Geographic patterns of species vulnerability	110
5.4.5	Climate refugia and multi-species conservation opportunities	110
5.4.6	Conservation implications and adaptive management.....	110
5.4.7	Limitations and future research directions.....	111
6	Chapter 6.....	112
6.1	Key Findings.....	112
6.1.1	Species exhibits highly specialized ecological requirements	112
6.1.2	Anthropogenic pressures as critical limiting factors in species distribution.....	113
6.1.3	Climate change–induced reductions in suitable habitats for the three species 114	
6.1.4	Identified potential climate refugia.....	115
6.2	Conservation recommendations.....	115
6.2.1	Immediate habitat protection and management	115
6.2.2	Threat mitigation strategies.....	117
6.2.3	Climate adaptation strategies	119
6.2.4	Species-specific conservation suggestions	120
6.3	Conclusion	121
7	References.....	124

List of Tables

LIST OF TABLES

Table 1 LULC Classes and Area Distribution	10
Table 2 Selected Variables for the analysis	46
Table 3 Generalized Linear Model Results of Jerdon's Babbler	48
Table 4 Random Forest Variable Importance for Presence of Jerdon's Babbler	50
Table 5 GLM Results for Presence of Black-breasted Parrotbill	53
Table 6 Random Forest Variable Importance for Presence of Black-breasted Parrotbill.	55
Table 7 GLM Results for Presence of Marsh Babbler.....	58
Table 8 Random Forest Variable Importance for Presence of Marsh Babbler.....	60
Table 9 Variable importance scores across different algorithms for Jerdon's Babbler species distribution model	89
Table 10 Variable importance scores across different algorithms for Black Breasted Parrotbill Babbler species distribution model.....	95
Table 11 Variable importance scores across different algorithms for marsh Babbler Babbler species distribution model.....	101
Table 12 Area (km ²) and percentage of climatic refuge categories by state.....	105

List of Figures

LIST OF FIGURES

Figure 1 Jerdon’s Babbler recorded in the study area (Photo: Harif P.).....	4
Figure 2 Black-breasted Parrotbill from the study area (Photo: Harif P.)	4
Figure 3 Marsh Babbler recorded in the study area (Photo: Jainy Maria).....	4
Figure 4 Map of the study area showing Land-Use and Land-Cover (LULC) classification.	10
Figure 5 Correlation Matrix of Environmental and Vegetation Variables	45
Figure 6 Dimensionality Reduction and Variable Contribution in Environmental Gradients Using Principal Component Analysis (PCA)	45
Figure 7 Model diagnostic plots for GLM predicting the presence probability of Jerdon’s Babbler.....	52
Figure 8 Spatial distribution of Jerdon’s Babbler presence and sampling sites along the study area.	52
Figure 9 Model Diagnostic Plots for GLM Predicting the Presence Probability of Black- breasted Parrotbill.	57
Figure 10 Spatial Distribution of Black-breasted Parrotbill Presence and Sampling Sites Along the study area.	57
Figure 11 Model Diagnostic Plots for GLM Predicting the Presence Probability of Marsh Babbler.....	62
Figure 12 Spatial Distribution of Marsh Babbler Presence and Sampling Sites Along the study area.	62
Figure 13 Fire Hotspot Zones Based on Frequency Analysis in the Study Area	72
Figure 14 Frequency of fire events across the landscape (2018–2023).....	72
Figure 15 Monthly trends in fire incidence across protected and non-protected landscapes	73
Figure 16 Seasonal variation in fire-affected area across protected and unprotected regions	73
Figure 17 Spatial distribution of fire-affected areas in grassland classes.....	73
Figure 18 Ecological Niche Models of the Current Distribution: A – Jerdon’s Babbler, B – Black-breasted Parrotbill, C – Marsh Babbler.....	93

Figure 19 Distribution of Jerdon’s Babbler Across Different SSP Scenarios and Time Periods.....	94
Figure 20 Effects of Climate Change on Jerdons Babbler’s Habitat Area under Varying Future Projections	94
Figure 21 Distribution of Black-breasted Parrotbill across different SSP scenarios and time periods.....	98
Figure 22 Effects of climate change on Black-breasted Parrotbill’s habitat area under varying future projections	98
Figure 23 Distribution of Marsh Babbler across different SSP scenarios and time periods	104
Figure 24 Effects of climate change on Marsh Babbler’s habitat area under varying future projections.....	104
Figure 25 Potential recovery sites identified for Jerdon’s Babbler.....	106
Figure 26 Potential recovery or refuge sites identified for Black-breasted Parrotbill	106
Figure 27 Potential recovery or refuge sites identified for Marsh Babbler	107
Figure 28 Combined potential refuges for all three study species under climate-induced habitat shifts across SSP scenarios	107

Chapter 1

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Overview of grassland ecosystems in Northeast India

Grassland ecosystems in Northeast India, especially the alluvial floodplain grasslands, represent highly dynamic and biologically rich habitats that support a diverse array of flora and fauna. These ecosystems are shaped by the seasonal flooding patterns of rivers like the Brahmaputra, which create a mosaic of wet and dry phases essential for the survival of many endemic and threatened species (Bhattachaiyya & Bora, 1997). Despite their significance, these ecosystems remain under-recognized and under-protected in national conservation frameworks (Pradhan et al., 2021a). Their fragmented distribution, complex successional patterns, and seasonal hydrological regimes make them uniquely adapted but highly vulnerable to anthropogenic change (Talbot et al., 2018).

The most prominent grasslands in this region are associated with the Brahmaputra and Barak River systems, occurring in floodplains, riverine islands, cut-off meanders, and toe slopes of the Himalayan foothills (“Brahmaputra and Barak Basin,” 2007). These ecosystems are typified by tall, dense grass species such as *Saccharum spontaneum*, *Imperata cylindrica*, *Phragmites karka*, and *Arundo donax*. They exhibit marked seasonal variation: submerged and silt-laden during the monsoon, and desiccated during the dry winter, which drives successional regeneration cycles. This hydrological dynamism fosters a patchy mosaic of grassland succession stages that provide critical nesting, foraging, and roosting habitats for specialized fauna.

Despite their ecological richness, the current status of these grasslands is alarming. Large tracts have been lost or degraded due to land conversion for agriculture, urban expansion, infrastructure development, and flood-control embankments that disrupt natural fluvial processes. Moreover, grasslands are often misclassified as 'wastelands' or transitional forests (Ravi & Krishnan, 2024), which precludes effective conservation action. Invasive alien species, especially *Mikania micrantha*, *Ipomoea carnea* and *Chromolaena odorata*, have further exacerbated habitat quality loss by outcompeting native grasses and

altering vegetation structure. Fire regimes, both natural and anthropogenic, are intensifying and often poorly timed, negatively affecting bird breeding cycles and regenerating grasses.

In recent decades, intact grassland ecosystems have become increasingly fragmented, surviving primarily in isolated patches within protected areas. Notable examples in Assam include Kaziranga, Dibru-Saikhowa, Orang National Park, Laokhowa-Burachapori, and Manas, which together harbour some of the most significant remnants of floodplain grasslands. In Arunachal Pradesh, smaller but ecologically important grassland patches persist in regions such as the Daying Ering Wildlife Sanctuary, and across East Siang, Lower Dibang Valley, and Lohit districts. These areas now serve as critical refuges for grassland-dependent species amidst growing anthropogenic pressures and land-use change. These regions represent the last strongholds for several threatened species dependent on tall wet grasslands, including Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler.

The study concentrates specifically on the grassland ecosystems of Assam and Arunachal Pradesh, focusing on the Brahmaputra floodplains and adjacent foothills, where habitat transitions occur rapidly and where the target species have historically been recorded (Parengal et al., 2025). Assam represents the core zone of extensive wet alluvial grasslands shaped by annual sedimentation and fluvial dynamics, whereas Arunachal Pradesh provides ecotonal zones where grasslands interface with semi-evergreen forests and evergreen forests in foothill valleys. These two states, therefore, offer contrasting yet complementary landscapes for understanding the habitat requirements, distribution dynamics, and conservation needs of grassland-specialist birds.

1.1.2 Importance of Brahmaputra floodplains

The Brahmaputra floodplains are among the most ecologically significant landscapes in South Asia, forming an expansive alluvial corridor that extends across Tibet (China), Northeast India, and Bangladesh. Within India, particularly in Assam and parts of Arunachal Pradesh, the Brahmaputra basin harbours a mosaic of habitats including grasslands, wetlands, riparian forests, oxbow lakes, and riverine islands, each dynamically shaped by annual monsoon flooding and sedimentation. These floodplains support exceptional biological richness (BirdLife International, 2025; Dutta & Sarma, 2023), including numerous endangered, endemic, and habitat-restricted species that are globally significant yet locally imperilled.

One of the defining features of the Brahmaputra floodplains is the presence of tall wet alluvial grasslands, which are increasingly rare across South and Southeast Asia. These grasslands are highly productive and seasonally dynamic, inundated by floodwaters during the monsoon and exposed during the dry season. This periodic disturbance drives a complex successional regime that supports specialized flora and fauna adapted to tall grass cover, fluctuating hydrology, and patchy habitat structure. Importantly, these grasslands are not seral stages of forest, but rather climax communities maintained by fluvial forces, grazing, and fire, making them ecologically unique and irreplaceable.

From a conservation perspective, the Brahmaputra floodplains are critical because they serve as last strongholds for several threatened and endemic species that are either grassland obligates or dependent on the floodplain mosaic for survival. These species are highly sensitive to habitat fragmentation, loss of tall grass cover, and hydrological changes. Unlike forest generalists, grassland specialists tend to exhibit low dispersal ability and strong site fidelity (Lanchier & Neuhauser, 2006), making them more vulnerable to local extirpations when habitat conditions are altered. The Brahmaputra floodplains are home to endangered fauna such as the Bengal Florican (*Houbaropsis bengalensis*), Swamp Francolin (*Ortygornis gularis*), Asian Elephant (*Elephas maximus*), and the iconic One-horned Rhinoceros (*Rhinoceros unicornis*), all of which utilize grass-dominated habitats for part of their life cycles.

In terms of endemism, the region is part of the Indo-Burma biodiversity hotspot, with several species found nowhere else in the world. Endemics such as the Black-breasted Parrotbill and Marsh Babbler reflect long-term ecological specialization and historical isolation of these floodplain ecosystems. Furthermore, the Brahmaputra floodplains are vital for ecological functions such as sediment trapping, nutrient cycling, groundwater recharge, and carbon sequestration. They buffer against floods, sustain wet-season agriculture, and support local livelihoods. Yet, despite their ecological and socioeconomic importance, these landscapes remain severely underrepresented in India's conservation frameworks. Most alluvial grasslands fall outside protected areas or are misclassified as degraded forests or wastelands, leaving them exposed to encroachment, unregulated grazing, infrastructural development, and invasion by exotic species.



Figure 1 Jerdon's Babbler recorded in the study area (Photo: Harif P.)



Figure 2 Black-breasted Parrotbill from the study area (Photo: Harif P.)



Figure 3 Marsh Babbler recorded in the study area (Photo: Jainy Maria)

1.1.3 Introduction to target species

1.1.3.1 Jerdon's Babbler (*Chrysomma alirostre*)

Jerdon's Babbler (Figure 1), a cryptic and habitat-specialist passerine bird, is an species of the tall wet grasslands and reedbeds of the Indian subcontinent. Belonging to the family Paradoxornithidae, Jerdon's Babbler is distributed in fragmented populations across several major riverine grassland systems of South and Southeast Asia. Its range includes isolated patches within the Indus basin in Pakistan, extending through disjunct populations across the Indo-Gangetic floodplains. The species is also present in the Brahmaputra valley of northeastern India, the Terai region of Nepal, and parts of western Myanmar. It exhibits a dorsal plumage brownish-olive, with rufous-buff underparts and a pale grayish-white throat. Face grayish with a distinct whitish orbital ring. Wings match the back in tone, lacking markings. Tail long, slender, and dark brown, slightly graduated.

Described and named by the British zoologist Thomas C. Jerdon, 1862 this babbler is strongly associated with *Saccharum*-dominated grasslands and prefers moist, tall vegetation often interspersed with water bodies. Such habitats are now among the most threatened ecosystems in Asia, with extensive loss due to agriculture, hydrological modifications, and fire mismanagement (Rahmani, 2012). Because of its narrow ecological requirements and declining habitat availability, Jerdon's Babbler is currently listed as Vulnerable on the IUCN Red List (BirdLife International, 2021).

The ecology and behaviour of *C. alirostre* remain inadequately studied, with most information arising from sporadic surveys and a few targeted monitoring efforts. Its sedentary nature and strong site fidelity make it particularly susceptible to local extinctions if habitats are degraded or fragmented. Notably, it was thought extinct in some areas until its rediscovery in regions like the Myanmar (Rheindt et al., 2014a).

1.1.3.2 Black-breasted Parrotbill (*Paradoxornis flavirostris*)

The Black-breasted Parrotbill (Figure 2), a rare and elusive passerine bird species, is one of the least studied members of the family Paradoxornithidae. Endemic to the dense grasslands of the Indian subcontinent, particularly in northeastern India and parts of Bhutan, this bird stands out for its distinctive appearance, rich rufous-brown plumage with

a slightly paler underside, a crown and upperparts of uniform colour, and a striking black facial mask stretching from the lores to the auriculars. This mask is bordered below by a white patch streaked with black, giving the bird a boldly patterned face. Its bill is thick, conical, and bright yellow, while the tail is notably long, broad, and rounded. Historically found across the Brahmaputra floodplain and adjacent regions, the species is now largely restricted to fragmented patches of suitable habitat, leading to growing concerns about its long-term survival.

This species has attracted significant conservation interest due to its sharply declining population and habitat specificity. It inhabits tall, wet grasslands an ecosystem that has faced extensive degradation and conversion for agriculture, settlements, and infrastructure development (Rahmani, 2012). Despite its striking appearance and conservation status, *P. flavirostris* remains poorly understood in terms of its breeding ecology, vocalizations, migratory patterns, and population dynamics.

1.1.3.3 Marsh Babbler (*Pellorneum palustre*)

The Marsh Babbler (Figure 3) is a poorly known and highly localized bird species endemic to the floodplain grasslands and scrub habitats of the Brahmaputra and Barak valleys in northeastern India and adjacent areas of Bangladesh. Belonging to the family Pellorneidae, it is distinguished by its rich brown upperparts tinged with rufous, particularly noticeable on the crown and nape. The facial pattern features a pale supercilium that contrasts sharply with a dusky eyestripe, while the underparts are whitish to pale grey, heavily streaked or mottled with dark brown along the breast and flanks. The wings and tail match the upperparts in colour, lacking distinct markings. Due to its elusive nature and restricted range, the species has long remained underrepresented in avian studies, despite its importance as an indicator of grassland ecosystem health.

The Marsh Babbler inhabits seasonally inundated tall grasslands, reedbeds, and scrubby edges of wetlands, habitats that are under intense pressure from agricultural expansion, flood control infrastructure, overgrazing, and invasive plant species (Rahmani, 2012). These grasslands are among the most threatened ecosystems in South Asia, and their degradation directly impacts the Marsh Babbler's population, which is believed to be declining. As a result, the species is currently classified as Vulnerable on

the IUCN Red List, highlighting the urgent need for habitat protection and restoration (BirdLife International, 2024b).

Unlike other babblers, *P. palustre* displays strong habitat fidelity and is largely non-migratory, which exacerbates its vulnerability to habitat fragmentation. Its distribution is patchy and largely confined to protected areas like D'Ering Memorial Wildlife Sanctuary, Dibru-Saikhowa National Park and Kaziranga National Park, but even within these reserves, grassland management is often inadequate or inconsistent (Allen, 2002; Rahmani et al., 2022). The Marsh Babbler is also understudied in terms of its breeding biology, population density, and ecological interactions, presenting significant gaps in ornithological knowledge and conservation planning.

Recent field surveys and citizen science efforts have led to sporadic new sightings, emphasizing the potential for rediscovery and ecological research in remnant grassland patches. However, sustained conservation outcomes depend on integrated strategies involving habitat mapping, community engagement, and restoration of natural flood regimes (Lahiri et al., 2022).

1.2 Research Gap and Significance

The alluvial grasslands of Northeast India, particularly those along the Brahmaputra floodplains in Assam and Arunachal Pradesh, are among the most ecologically significant yet under-researched ecosystems in the Indian subcontinent. These grasslands support a suite of specialized and often endemic avifauna, including the Vulnerable Jerdon's Babbler (*Chrysomma altirostre*), the Black-breasted Parrotbill (*Paradoxornis flavirostris*), and the Marsh Babbler (*Pellorneum palustre*). Despite their conservation importance, there exists a substantial knowledge gap concerning the current distribution, habitat preferences, and population dynamics of these species.

Previous studies have primarily focused on general avian diversity within protected areas, leaving the specific habitat requirements and threats faced by grassland specialists inadequately addressed. Moreover, the dynamic nature of floodplain ecosystems, characterized by seasonal inundation and sediment deposition, necessitates a nuanced understanding of habitat availability and quality, which is currently lacking.

Given this exceptional biodiversity, the riverine grassland of Assam and Arunachal Pradesh, especially those bordering the Brahmaputra basin, represent key habitats for species such as the Black-breasted Parrotbill and Marsh Babbler, which are highly habitat-specific and sensitive to environmental changes. The current study places emphasis on understanding the distribution, ecological requirements, vulnerability and potential population recovery sites of these species in the grasslands and riparian zones of Assam and Arunachal Pradesh, areas that remain largely under-surveyed in ornithological literature and conservation assessments.

The significance of this study lies in its targeted approach to fill these critical knowledge gaps by our objectives. So, the study aims to contribute significantly to the conservation biology of grassland birds in Northeast India, providing a scientific basis for effective management and protection of these vulnerable species and their habitats.

1.3 Research Objectives

- i. *To assess the habitat characteristics of three select threatened grassland birds namely Jerdon's Babbler, Black-breasted Parrotbill and Marsh Babbler.*
- ii. *To evaluate the threats to these select three species of birds and their habitats.*
- iii. *To predict the current and future potential habitats of these birds and find potential population recovery sites.*

1.4 Thesis Structure Overview

The Ph.D. thesis, is structured to systematically investigate the ecological needs, threats, and conservation prospects of three key avian species: Jerdon's Babbler (*Chrysomma altiloquax*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*). The thesis is organized into six core chapters along with references and appendices.

Chapter 1 serves as the introduction, offering a comprehensive overview of grassland ecosystems in Northeast India, particularly the Brahmaputra floodplains, and contextualizing the ecological importance of the target species. It outlines the research gaps, justifies the significance of the study, and states the research objectives. The study

area, Assam and Arunachal Pradesh is described in terms of vegetation, geomorphology, climate, and biodiversity. Chapter 2 reviews existing literature on the grassland ecosystems of the Brahmaputra Valley, the ecology of the focal species, habitat requirements, conservation threats, and relevant methodological approaches such as species distribution modelling and the effects of climate change on avifauna.

Chapter 3 focuses on habitat characterization, describing methods employed in field surveys and presenting results on vegetation structure and environmental parameters, followed by a detailed discussion and conclusions. Chapter 4 evaluates both direct and indirect threats facing the species and their habitats, integrating a vulnerability analysis and conservation challenges. Chapter 5 centres on predictive habitat modelling using ensemble Species Distribution Models (SDMs), highlighting current and projected distributions under different climate scenarios and identifying sites for potential population recovery. Chapter 6 synthesizes the findings, outlines conservation recommendations, and discusses broader management implications.

The thesis concludes with a comprehensive reference list and supplementary appendices, ensuring that the research adheres to academic standards and contributes effectively to conservation science. This structured format facilitates a logical progression from background information through analysis to actionable insights, aligning with the regulatory framework prescribed by the affiliated university.

1.5 Study Area Description

The present study was carried out in the floodplains of the Brahmaputra River, spanning across the states of Assam and Arunachal Pradesh in Northeast India (Figure 4). The Brahmaputra basin originating from the Tibetan Plateau and crossing the Eastern Himalayas before meandering through the vast alluvial plains of Assam and finally entering Bangladesh. The region harbours expansive riparian and semi-terrestrial habitats, prominently characterized by seasonally inundated grasslands, riverine forests, and alluvial islands. These habitats are crucial for the survival of several endemic and threatened avian species, including the three focal species of this study: Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*).

Geographically, this region includes floodplain landscapes interspersed with natural levees, oxbow lakes, river channels, and sandbars. The area supports annual monsoonal flooding, which shapes the hydrology and productivity of the landscape. This hydrological dynamism leads to successional mosaics of vegetation and plays a pivotal role in sustaining the wet alluvial grassland ecosystems the primary habitats for the study species.

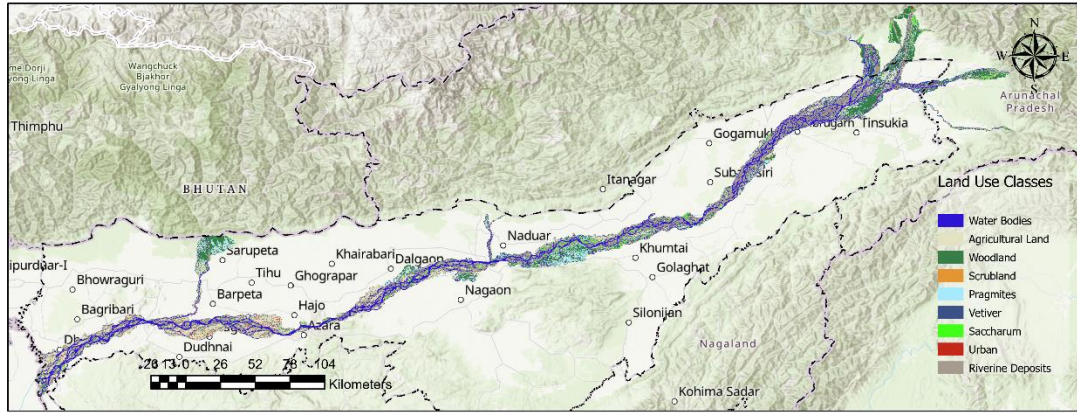


Figure 4 Map of the study area showing Land-Use and Land-Cover (LULC) classification.

Table 1 LULC Classes and Area Distribution

LULC CLASS	AREA (KM ²)	PERCENTAGE (%)	DESCRIPTION
NO DATA	0.009	0.0001	Areas with insufficient data or cloud cover
WATER BODIES	1,965.13	21.2	Rivers, lakes, ponds, and seasonal wetlands
AGRICULTURAL LAND	1,894.18	20.4	Cultivated areas including rice paddies and crop fields
WOODLAND	947.83	10.2	Dense forest areas and tree plantations
SCRUBLAND	10.35	0.1	Sparse vegetation and degraded forest areas
PHRAGMITES	506.20	5.5	Reed beds dominated by common reed species
VETIVER	726.02	7.8	Tall grass habitats dominated by vetiver grass

LULC CLASS	AREA (KM ²)	PERCENTAGE (%)	DESCRIPTION
SACCHARUM	379.61	4.1	Areas dominated by Saccharum grass species
BUILT-UP	113.88	1.2	Areas dominated by human settlement
RIVERINE DEPOSITS	3,089.32	33.3	Sand bars, alluvial deposits, and bare riverine areas
TOTAL STUDY AREA	9,271.57		

1.5.1 Assam

Assam forms the core of the middle and lower Brahmaputra floodplains and constitutes the primary landscape for floodplain grassland habitats in Northeast India. Its unique biogeographical positioning, climatic conditions, and annual fluvial dynamics make it a critical habitat zone for several threatened avian species, including those studied in this research.

1.5.1.1 Vegetation

The state supports a variety of forest types shaped by topography, rainfall, soil, and biotic interference. Tropical evergreen forests are primarily distributed across the Assam Valley, Upper Assam, and parts of Cachar (Champion & Seth, 1968). These forests feature dense canopy layers dominated by species such as Dipterocarpus, Mesua, and Shorea, accompanied by abundant bamboo and cane brakes (A. Saikia, 2011).

Semi-evergreen forests, often a mosaic of evergreen and deciduous species, are prevalent in the central Assam Valley (A. Saikia, 2011). These forests have a somewhat open and broken canopy structure compared to the tropical evergreen type. The tree strata include large buttressed trees, a rich middle layer, and an understorey comprising canes, woody climbers, and lianas. The canopy gaps allow ample sunlight, fostering vigorous growth of shrubs and herbaceous plants.

Moist deciduous forests dominate the central and lower parts of Assam, especially in districts such as Nagaon and Morigaon (A. Saikia, 2011). These forests are typically classified into Sal-dominated forests (*Shorea robusta*) and mixed deciduous forests, which

also include species such as *Terminalia*, *Dillenia*, and *Lagerstroemia*. They support both timber and non-timber forest products and are highly influenced by anthropogenic activities such as logging and shifting cultivation.

In addition to wooded areas, Assam supports extensive grassland ecosystems, especially in low-lying alluvial tracts and floodplains (Table 1). These grasslands develop on cut-off river meanders, abandoned channels, and riverine islands (chars), particularly in the eastern Assam Valley. Subjected to seasonal flooding of up to 3 meters during the monsoon and subsequent drying on Khurkani soils in the summer, these areas inhibit tree growth but promote dense herbaceous vegetation. Tall grasses such as *Saccharum spontaneum*, *Phragmites karka*, and *Arundo donax* may exceed 5 meters in height. These habitats serve as critical refugia for species such as the one-horned rhinoceros (*Rhinoceros unicornis*) and Asian elephant (*Elephas maximus*) (Ghosh et al., 2024; Vasudev et al., 2021).

Such grassland-savanna mosaics are particularly prominent in protected areas including Kaziranga National Park, Pobitora Wildlife Sanctuary, Orang, Sonai-Rupai, Laokhowa, Barnadi, Burachapori, and Dibru-Saikhowa, as well as parts of Manas National Park. These landscapes support high faunal diversity and are of immense conservation value for avifaunal species dependent on tall grass habitats.

Additionally, subtropical broadleaf hill forests and pine forests occur in the upland districts of Karbi Anglong and Dima Hasao (Sharmah & Jha, 2014), reflecting the transitional biogeography with the Indo-Burmese hill tracts. The littoral and swamp forests, once widespread along floodplains, have largely degraded due to agricultural expansion and human settlements (Shah & Dutta, 2024).

1.5.1.2 Geomorphology

The geomorphology of Assam is shaped by its unique position between the eastern Himalayas and the tectonically dynamic Indo-Burman ranges, with the Brahmaputra and Barak River systems exerting a dominant influence. Five primary geomorphic zones define its terrain (Kunte, 1988):

1. Brahmaputra Floodplains

Extending 5 - 20 km wide, these dynamic alluvial plains are shaped by sediment-rich, slow-moving waters. The region frequently forms mid-channel Islands, known as chars, fostering grassland development through sediment accretion.

2. Assam Alluvial Plains

Created by tributaries of the Brahmaputra and Barak, these fertile floodplains are characterized by oxbow lakes, meander scars, and relict channels. While agriculturally productive, they are prone to erosion and seasonal flooding.

3. Mikir Denudational Hills

A dissected outlier of the Peninsular Plateau, the Mikir Hills exhibit rugged topography formed from granitic and metamorphic rocks. They represent prolonged denudation and uplift processes, contributing to local landscape complexity.

4. Naga Piedmont Plains

Situated along the foothills of the Naga Hills, this transitional zone features coarse alluvial fans and active drainage systems, serving as critical recharge zones and ecological buffers.

5. Naga Structural Hills

Marked by strike ridges, cuestras, and fault-controlled valleys, these hills form part of the active Indo-Burman geosynclinal belt. Their complex tectonic behaviour often results in landslides and slope instability.

These geomorphic settings underpin the ecological heterogeneity of Assam, influencing the distribution of critical habitats such as wetlands, grasslands, and riparian forests (Sarma, 2005).

1.5.1.3 Climate

Assam, located in the northeastern part of India, exhibits a humid subtropical climate (Köppen classification Cwa) characterized by high humidity, abundant rainfall, and distinct seasonal variations. Its climate is largely influenced by the southwest monsoon,

topographical diversity, and the presence of the Brahmaputra and Barak river valleys (Das et al., 2009).

The state experiences three primary seasons: summer (March to May), monsoon (June to September), and winter (October to February). Summer temperatures in Assam generally range between 25°C and 35°C, while winter temperatures can drop to around 6°C in certain regions. The average annual rainfall ranges from 1,500 mm to 3,800 mm, with the monsoon period contributing approximately 70% - 80% of the total annual precipitation (IMD, 2021).

The frequency and intensity of floods have increased in recent decades due to a combination of factors, including increased rainfall variability, glacial melt contributions, deforestation, siltation of riverbeds, and climate change (Chakraborty et al., 2025). Usually, the Brahmaputra flood two time per year due to snowmelt and monsoon rains (Kamal et al., 2024). In recent decades, studies have indicated a noticeable rise in average temperatures and variability in monsoon onset and withdrawal dates (Alam et al., 2024). The state has also witnessed a growing frequency of extreme weather events, such as intense rainfall and prolonged dry spells. These climatic anomalies pose significant threats to both natural ecosystems and socio-economic stability (Bhuyan & Deka, 2024).

1.5.1.4 Assam's Fauna and Flora

The state of Assam, forming a major part of Northeast India's Indo-Burma biodiversity hotspot, harbours one of the richest assemblages of flora and fauna on the Indian subcontinent. This region exhibits exceptionally high levels of endemism, particularly among vascular plants, orchids, amphibians, birds, and primates (Khyanjeet Gogoi, et al., 2024; Lasushe et al., 2024; Trivedi et al., 2025), making it a globally recognized centre of species richness and evolutionary diversity.

Flora

The state's unique geographical location and varied physiography have given rise to a wide range of ecosystems including tropical rainforests, deciduous forests, swamps, and grasslands. This ecological diversity supports a rich and varied flora, consisting of numerous endemic, rare, and economically important species. Scientific investigations into

the flora of Assam reveal a remarkable diversity of vascular plants and angiosperms. A detailed study conducted in the Barail Wildlife Sanctuary identified over 300 species of angiosperms, including rare plants such as *Cymbidium elegans* and *Litsea glutinosa*, underscoring the conservation significance of the region (Bhattacharyya & Bora, 2018). Similarly, the Behali Reserve Forest was documented to harbour 382 vascular plant species, with endemic taxa like *Dipterocarpus retusus* and *Magnolia hodgsonii* being assessed under IUCN Red List criteria (Borah et al., 2020). The alluvial floodplain grasslands, dominated by tall grasses such as *Saccharum spontaneum*, *Imperata cylindrica*, and *Themeda arundinacea*.

The Chirang Reserve Forest in the Bodoland Territorial Region adds significantly to Assam's botanical wealth, with an inventory of 728 plant taxa representing 138 families, including threatened species such as *Gnetum gnemon* (Basumatary, 2023). Ethnobotanical studies further highlight the cultural and medicinal relevance of Assam's flora. Plants like *Clerodendrum colebrookianum* and *Centella asiatica* are integral to traditional healthcare practices among indigenous communities such as the Bodos and Mishings (Agarwal et al., 2021). A digitized dataset of medicinal plants from Assam includes 117 species with vernacular names and uses, offering a vital resource for pharmacological and conservation research (Sarma et al., 2023).

Fauna

The state's fauna includes a wide spectrum of taxa ranging from large mammals and endemic birds to amphibians, reptiles, and a significant variety of invertebrates. Prominent protected areas such as Kaziranga National Park, Manas National Park, and Dibru-Saikhowa Biosphere Reserve play a critical role in sustaining many endangered and endemic species. Kaziranga, a UNESCO World Heritage Site, is globally renowned for harbouring the largest population of the Indian one-horned rhinoceros (*Rhinoceros unicornis*), besides being home to elephants, tigers, wild buffaloes, and swamp deer (Gogoi & Gogoi, 2022; Islam et al., 2022). Manas National Park, another World Heritage Site, shelters rare species such as the golden langur (*Trachypithecus geei*), pygmy hog (*Porcula salvania*), and hispid hare (*Caprolagus hispidus*) (Nath et al., 2010).

Assam's avifauna is among the richest in India, comprising over 900 recorded bird species due to its diverse habitats ranging from wetlands and grasslands to tropical forests (Sinha et al., 2012). Key regions such as Kaziranga, Manas, and Dibru-Saikhowa are designated as Important Bird Areas (IBAs), hosting globally threatened species like the Bengal florican (*Houbaropsis bengalensis*) and the white-winged wood duck (*Asarcornis scutulata*) (Rajendra Joshi et al., 2014). The greater adjutant stork (*Leptoptilos dubius*), once near extinction in India, now survives largely due to community-led conservation efforts near Guwahati (Narasimmarajan et al., 2014). Migratory birds such as bar-headed geese and ruddy shelducks also use Assam's wetlands as critical wintering sites, with Satajan and other wetlands in Lakhimpur District serving as key habitats (Siddhartha Suman Bora, et al., 2024). Hornbills, including the great hornbill (*Buceros bicornis*), further enrich forest biodiversity. However, habitat loss, pollution, and disturbance from human activity remain serious threats. Conservation strategies now incorporate satellite tracking, acoustic monitoring, and grassroots engagement to better protect this avian wealth (Chakdar et al., 2019).

Assam's grasslands, particularly in Manas and Kaziranga National Parks, are crucial habitats for several globally threatened bird species. Among them, the Bengal florican (*Houbaropsis bengalensis*), listed as Critically Endangered, is a flagship species. Recent surveys in Manas recorded 50 males and 17 females, reflecting a modest population increase, but threats like habitat succession, invasive species, and grazing persist (Thakur et al., 2024). Other threatened species dependent on these grasslands include the Greater adjutant stork (*Leptoptilos dubius*) and Swamp francolin (*Francolinus gularis*), both facing pressures from habitat degradation and encroachment (Narasimmarajan et al., 2013). Effective conservation requires restoring grassland ecosystems through fire management, limiting livestock intrusion, and engaging local communities.

In the herpetofaunal domain, a survey in Amchang Wildlife Sanctuary recorded 41 species of reptiles, including pit vipers and skinks, and 22 species of amphibians, several of which are under IUCN concern or remain unevaluated (Purkayastha et al., 2020). Amphibian diversity across the state now exceeds 70 documented species, many endemic to the Northeast Himalayan and Eastern hill ranges. On the ichthyofaunal front, Assam's

aquatic ecosystems, particularly the Brahmaputra and Barak river basins, support over 200 freshwater fish species, including Cypriniformes as the dominant group (Goswami & Singha, 2023).

1.5.2 Arunachal Pradesh

1.5.2.1 Vegetation

Arunachal Pradesh, situated at the northeastern tip of the Eastern Himalayas, exhibits a remarkable ecological gradient from the snow-clad margins of the Tibetan Plateau in the north to the humid Brahmaputra plains in the south. Bordered by Bhutan and Myanmar, the state lies at the confluence of the Himalayan, Indo-Malayan, and Indo-Burmese phytogeographic zones, fostering exceptional plant diversity and endemism (Kanwal & Lodhi, 2018).

According to the India State of Forest Report (ISFR) 2021, forests cover approximately 79.67% of Arunachal Pradesh's geographical area, amounting to 65,882 square kilometres (India State of Forest Report, 2023). This extensive forest cover represents a complex mosaic shaped by elevation, climate, and soil. The state's forests are categorized into five major types based on altitude:

1. Tropical Forests (up to 900 m): These include evergreen species such as *Dipterocarpus*, *Artocarpus*, *Alstonia*, and *Mesua*, along with semi-evergreen subtypes found in low hills and riverine zones.
2. Subtropical Forests (900–1,800 m): Comprising broadleaf species like *Quercus*, *Castanopsis*, *Schima*, and pine forests dominated by *Pinus roxburghii*.
3. Temperate Forests (1,800–3,000 m): Featuring broadleaf species such as *Acer*, *Betula*, *Rhododendron*, and coniferous species like *Abies densa* and *Picea smithiana*.
4. Sub-alpine Forests (3,000–4,000 m): Dominated by *Juniperus* and *Betula utilis*, transitioning into rhododendron thickets.
5. Alpine Vegetation (above 4,000 m): Characterized by herbaceous meadows with genera like *Primula*, *Anemone*, *Saussurea*, and *Meconopsis*.

Secondary vegetation formations, particularly near settlements and areas of shifting cultivation, include degraded forests, bamboo brakes (with 89 species), open scrub, and aquatic flora in oxbow wetlands of the Siang, Lohit, and Tirap valleys (Taro, 2021).

The region is recognized as a global biodiversity hotspot, supporting over 500 species of orchids, 500 medicinal plants, and 400 wild edible plant species, all integral to Indigenous livelihoods (Kanwal & Lodhi, 2018).

Grasslands in Arunachal Pradesh, though often overshadowed by the region's dense forests and alpine zones, constitute vital ecological niches supporting unique biodiversity and sustaining pastoral and agro-pastoral communities. These grasslands, primarily found in intermontane valleys, floodplains, and high-altitude zones, exhibit diverse floral compositions adapted to the state's varied altitudinal and climatic gradients. Grass species such as *Saccharum spontaneum*, *Imperata cylindrica*, and bamboo brakes dominate these ecosystems, particularly in transitional zones between forest and cultivated lands (Areendran et al., 2018; Rawat & Adhikari, 2015).

1.5.2.2 Geomorphology

Arunachal Pradesh, located in the easternmost part of the Indian Himalayas, exhibits a complex geomorphology shaped by intense tectonic forces, fluvial activity, and diverse lithological structures. This mountainous state is bisected by major thrust systems such as the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT), which actively influence the region's landforms and river dynamics (Luirei & Bhakuni, 2009). The topography ranges from low-lying foothills in the south (~50 m) to high-altitude glaciated peaks exceeding 7,000 m in the north, resulting in a dramatic altitudinal gradient that governs climatic and geomorphic diversity.

The geomorphic setting includes deeply incised river valleys, steep escarpments, unpaired terraces, and paleochannels that collectively reveal ongoing neotectonic activity. In areas such as Pasighat and Roing-Balek, the Siang River and its tributaries display anomalous drainage patterns and abrupt shifts in channel orientation, attributed to ground tilting and fault-controlled flow diversions (Luirei & Bhakuni, 2009; Maji et al., 2001). These tectonically driven changes not only mold the landscape but also influence sediment transport, floodplain evolution, and agricultural suitability.

Morphometric analysis of river basins like the Digaru in Lohit district further illustrates the dynamic fluvial regime, marked by variable drainage densities, stream gradients, and sediment loads that reflect underlying tectonic controls and erosional processes (Chai, 2014). The geomorphic heterogeneity of Arunachal Pradesh underscores the importance of integrating geological, hydrological, and remote sensing data for effective watershed management and disaster risk mitigation in this seismically active region.

Grassland ecosystems in Arunachal Pradesh are primarily found in the floodplains and the transitional zones between forests and cultivated lands. These areas arise naturally or are maintained through anthropogenic activities like shifting cultivation and seasonal burning. Notably, the Daying Ering Wildlife Sanctuary in East Siang District has witnessed a 25% reduction in grassland cover over the past decade due to fluvial expansion and land-use change, highlighting the vulnerability of these ecosystems to geomorphological and anthropogenic pressure (Mayi et al., 2023).

The role of slope and altitude is particularly influential. In West Kameng District, less than 0.1% of the total land is classified as grassland, with the majority of land use dominated by forests, wastelands, and steep slopes that limit grass proliferation (Posti & Baruah, 2020). Grassland persistence is thus heavily dependent on moderate slopes and well-drained colluvial soils typically found in valley bottoms and alluvial terraces. As such, understanding the geomorphic controls on grassland formation is essential for sustainable land-use planning, conservation strategies, and habitat management in the Eastern Himalayas.

1.5.2.3 Climate

Arunachal Pradesh, situated in the Eastern Himalayas, ranks among the highest rainfall-receiving states in India, characterized by significant spatial and seasonal variability in precipitation. Annual rainfall in the state ranges from approximately 1,000 mm in high-altitude alpine zones to over 5,750 mm in the southern foothill districts such as Papum Pare, Lower Subansiri, and East Siang (Sandeep et al., 2023). The average annual precipitation across the state exceeds 3,500 mm, with more than 70% of this total occurring during the southwest monsoon season, which typically spans from

May to September (Patle et al., 2016). Orographic effects strongly influence this distribution, with the windward slopes of the Eastern Himalayas and Indo-Burmese ranges receiving intense and prolonged monsoonal showers, while leeward and higher-altitude regions experience a rain-shadow effect and comparatively lower precipitation (Sandeep et al., 2023).

Climatic conditions exhibit marked variation across the state's elevational gradient. In the mid-tropical and subtropical plains, summer temperatures frequently exceed 38 - 40°C, contributing to high evapotranspiration rates, influencing vegetation patterns and crop water demand (Drema et al., 2024). In contrast, temperate and alpine zones located above 2,500 meters particularly in districts like Tawang, Upper Subansiri, and West Kameng experience sub-zero temperatures during winter (December to February), often accompanied by snowfall and persistent frost. Monsoonal temperatures across the state generally range from 22°C to 33°C, while winter averages in the lowland zones fall between 6°C and 21°C, depending on elevation and geographical position (Drema et al., 2024).

Humidity levels remain elevated throughout the monsoon period, often exceeding 80%, which facilitates the proliferation of dense evergreen forests, high biomass grasslands, and wetland systems. These conditions are vital for the sustenance of Arunachal Pradesh's complex ecological mosaics, including its moist deciduous forests, braided river systems, and floodplain grasslands. Such habitats are especially critical for numerous endangered and endemic avifauna, many of which depend on the seasonal abundance of aquatic and terrestrial resources for breeding and foraging. The hydrological rhythm driven by the monsoon also maintains sediment transport, nutrient cycling, and successional dynamics in floodplain ecosystems such as those found along the Brahmaputra basin (Patle & Libang, 2014).

1.5.2.4 Fauna and Flora

Arunachal Pradesh, located at the confluence of the Eastern Himalayas and Indo-Burmese biodiversity realms, is internationally recognized as one of the 36 global biodiversity hotspots. Its exceptional topographic and climatic heterogeneity, ranging from subtropical valleys to alpine meadows, has fostered a remarkable concentration of endemic,

rare, and evolutionarily significant species. The state is considered one of India's most biodiverse regions, often referred to as a "biodiversity cradle" in South and Southeast Asia.

Flora

Arunachal Pradesh, often referred to as the "Orchid State of India," is endowed with an extraordinary floral richness due to its complex topography, wide altitudinal range, and location within the Eastern Himalayan biodiversity hotspot. The state's vegetation transitions from tropical evergreen forests in the foothills to temperate coniferous forests and alpine meadows in the higher elevations (Kanwal & Lodhi, 2018), creating diverse ecological niches that support over 4,000 species of flowering plants, including more than 450 species of orchids (Hegde, 2020; Saikia et al., 2017). Major forest types include tropical semi-evergreen, sub-tropical broadleaf, temperate mixed broadleaf, and alpine scrub forests, each hosting a variety of ecologically significant and endemic species (Saikia et al., 2017). Noteworthy among these are *Rhododendron arboreum*, *Michelia champaca*, *Tsuga dumosa*, and *Taxus wallichiana*.

The state's orchid flora includes both epiphytic and terrestrial forms, with genera such as *Dendrobium*, *Paphiopedilum*, and *Bulbophyllum* contributing to its global botanical importance (Hegde, 2020). In addition to orchids, Arunachal Pradesh is home to numerous economically and ethnobotanically important species used by indigenous communities for food, fibre, medicine, and ritual purposes. Forested regions like Namdapha and Pakke Tiger Reserves represent key conservation landscapes for the preservation of native flora.

Fauna

The state harbours over 879 species of birds (Neelam Yania et al., 2021), 200 species of mammals (Kumar, 2018), and a rich diversity of reptiles, amphibians, and invertebrates, many of which are endemic or threatened (Kumar, 2015). Notably, it is home to iconic and rare mammals such as the red panda (*Ailurus fulgens*), Mishmi takin (*Budorcas taxicolour taxicolour*), clouded leopard (*Neofelis nebulosa*), Western Hoolock Gibbon (*Hoolock hoolock*), Stump-tailed Macaque (*Macaca arctoides*), Slow Loris (*Nycticebus bengalensis*), and the elusive snow leopard (*Panthera uncia*) in higher

elevations (Barman et al., 2024; Bhatnagar et al., 2024; Joshi et al., 2021; Selvan et al., 2014), as well as the recently described Arunachal macaque (*Macaca munzala*) in mid-elevation forests (Sinha et al., 2006).

The avifauna is equally remarkable, with species such as the Bugun liocichla (*Liocichla bugunorum*), a critically endangered bird endemic to the Eaglenest Wildlife Sanctuary and the endangered Blyth's tragopan (*Tragopan blythii*), making the state a global priority for bird conservation (Ghosh-Harihar et al., 2019), also hosts unique grassland bird communities, particularly in floodplain and riverine habitats like the D'Ering Memorial Wildlife Sanctuary. This sanctuary, situated in the Siang River basin, is one of the finest examples of wet grassland ecosystems in Northeast India and supports a range of threatened avian species. It harbours the Critically Endangered Bengal Florican (*Houbaropsis bengalensis*), as well as globally threatened species such as the Black-breasted Parrotbill (*Paradoxornis flavirostris*), Marsh babbler (*Pellorneum palustre*), Swamp Francolin (*Francolinus gularis*), Swamp Grass-Babbler (*Liticilla cinerascens*), and Jerdon's Babbler (*Chrysomma altirostre*) (Rahmani et al., 2022). Several major rivers like the Siang, Dibang, and Lohit, along with their riparian zones and floodplains, also support semi-aquatic fauna including the endangered white-bellied heron (*Ardea insignis*) and numerous freshwater fish and amphibian species (Menzies et al., 2021). The overlap of tropical lowlands and alpine meadows supports complex ecological interactions and seasonal faunal migrations, further enriching the biodiversity mosaic of the region.

Herpetofaunal diversity is considerable, though still underexplored, with numerous species awaiting formal description. The region's varied microclimates support a wealth of amphibians and reptiles, many of which are endemic and exhibit strong niche specificity. Aquatic systems such as montane streams and floodplain wetlands harbour a variety of native fish species and invertebrates, many of which play vital roles in local food security and nutrient cycling.

Chapter 2

CHAPTER 2

LITERATURE REVIEW

The Brahmaputra River system represents one of the world's most biodiverse yet understudied grassland ecosystems, supporting critical habitat for numerous threatened avian species (Jahan et al., 2022a; Narasimmarajan et al., 2013). Recent research reveals that grassland birds face the most severe population declines of any terrestrial bird group globally (Daskalova et al., 2020), with species endemic to South Asian river systems experiencing particularly acute threats from habitat conversion and climate change (Jahan et al., 2022a). The Brahmaputra's tropical riverine grasslands serve as irreplaceable habitat for specialists like Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*). Effective conservation strategies for the Marsh Babbler can only be developed through a comprehensive understanding of the complex interactions among seasonal flooding regimes, vegetation dynamics, and anthropogenic pressures. This review establishes the scientific foundation for distribution modelling and conservation strategies by examining ecosystem processes, species ecology, habitat requirements, conservation challenges, modelling methodologies, and climate change impacts across global grassland systems.

2.1 Grassland Ecosystems of the Brahmaputra Valley

2.1.1 Ecosystem structure and dynamics

The Brahmaputra floodplains encompass the majority of protected grassland habitats in northeastern India, representing one of Earth's most productive tropical grassland systems (Sharma et al., 2023). These dynamic ecosystems are characterized by extensive alluvial grasslands created by the seventh-largest river system globally, which maintains two distinct grassland types based on inundation duration: Short Grasslands (SG) in areas with prolonged flooding and Tall Grasslands (TG) in zones with shorter inundation periods (Sharma et al., 2023). This hydrological distinction fundamentally shapes vegetation structure, species composition, and ultimately habitat suitability for grassland-dependent birds.

Recent comprehensive studies monitoring 1,152 plots over two years revealed that grassland characteristics are primarily controlled by seasonal flooding patterns, with longer inundation periods promoting short grassland development and higher plant species diversity (Sharma et al., 2023). The Brahmaputra exhibits extreme seasonal variation, with an average annual discharge of approximately 20,000–22,000 m³/s rising to flood peaks around 98,000–103,000 m³/s during the monsoon season (June–October), when 70–85% of its ~2,300–2,500 mm annual rainfall occurs. This flood pulse drives the formation of distinctive grassland mosaics essential for supporting diverse bird communities (Hossain et al., 2021; Palash et al., 2023).

2.1.2 Vegetation communities

The grassland flora comprises diverse communities dominated by reeds, sedges and grasses forming the largest vegetation component. Key grass species include *Phragmites karka*, *Apluda mutica*, *Sclerostachya fusca*, *Saccharum* species in tall grass communities, and *Cynodon* species in short grass areas (Khatri & Barua, 2011). Associated flora encompasses *Ageratum conyzoides*, *Alpinia* species, *Amaranthus* species, and numerous other herbaceous plants (Devi et al., 2022) creating microhabitat diversity crucial for grassland birds.

Comparative research from Bangladesh's portion of the system documented 31 grassland specialist bird species dependent on specific vegetation communities, with nine species classified as obligate tall grass breeders requiring optimum vegetation heights (Jahan et al., 2022a). This finding emphasizes the critical importance of maintaining diverse vegetation structure across the landscape, as different bird species exhibit distinct microhabitat preferences within the broader grassland matrix.

2.1.3 Soil processes and nutrient dynamics

The fertile alluvial soils deposited from Himalayan and Tibetan sources create the foundation for grassland productivity. Predominant soil types include red loamy soil, alluvial soil, and sandy-loamy-clayey combinations with laterite soils in some areas (Walia & Chamuah, 1992). Detailed studies reveal that carbon, nitrogen, phosphorus, and potassium concentrations vary significantly between grassland types and management

regimes, with grazing exclusion increasing soil nutrient content through enhanced litter accumulation while controlled burning reduces woody growth and enhances soil nutrient conditions (Sharma et al., 2023).

2.1.4 Human impacts

Contemporary land-use analysis reveals escalating anthropogenic pressures. Between 1913 and 2023, agricultural land expanded by approximately 15%, while forest cover declined by about 10%, accompanied by a significant reduction in grassland areas (Saeed et al., 2025). Major threats include sand mining activities (Daham et al., 2024), urbanization (Pradhan et al., 2021b), uncontrolled burning, grazing, invasive species introduction, and woody encroachment from fire suppression (Sharma et al., 2023). These pressures create habitat fragmentation affecting species dependent on undisturbed ecosystems while promoting human-wildlife conflict in protected areas (Jahan et al., 2022a).

2.1.5 Global comparisons

Comparative analysis of major riverine grasslands reveals unique ecological and conservation challenges in the Brahmaputra floodplains. Unlike the extensively modified Mississippi River Basin (with over 80% of its floodplains altered) or the policy-supported Danube restoration projects (Friberg et al., 2017), the Brahmaputra grasslands are undergoing rapid degradation with minimal large-scale restoration (Sharma et al., 2023). Their tropical, monsoon-driven hydrology sets them apart from the snowmelt-fed, temperate systems of the Mississippi and Danube (Hein et al., 2016). This, coupled with their exceptional biodiversity, including globally significant endangered species, amplifies the urgency for conservation.

2.2 Ecology of Jerdon's Babbler

The species *Chrysomma altirostre* was first described by Thomas C. Jerdon, in 1862, based on a pale reddish-brown individual collected near Thayetmyo in northern Myanmar. Three subspecies are recognized: the nominate *C. a. altirostre* (Myanmar floodplains), *C. a. griseigularis* (Terai of Nepal/Northeast India), and *C. a. scindicum* (Indus basin, Pakistan) (Parengal et al., 2025).

These species occur in three highly fragmented populations across South Asia: the Indus basin (Pakistan), the Terai region of Nepal and northern India, and the Brahmaputra, Arunachal region, extending into Myanmar's Irrawaddy - Sittang floodplains (Parengal et al., 2025). The species inhabits seasonally inundated floodplain reedbeds and tall wet grasslands at low elevations, with a strong association to dominant vegetation such as *Phragmites*, *Imperata*, *Saccharum*, and *Typha* species (Sadanandan et al., 2018). Recent genetic studies by Sadanandan et al. (2018) found limited mitochondrial divergence across subspecies despite geographic barriers, suggesting historical connectivity with ecomorphological adaptations in westernmost populations. The species demonstrates extreme habitat specialization requiring dense reedbeds and tall grasslands, particularly *Phragmites* (common reed), *Typha* (reedmace), *Imperata cylindrica* (cogongrass), and *Saccharum spontaneum* (kans grass) several meters in height on wet substrates.

Measuring 16–17 cm in length, adult Jerdon's Babbler exhibit predominantly buffy chestnut-brown upperparts and paler yellowish-brown underparts. The lores, throat, and breast are greyish, while the tail and a patch on the wings are more rufescent. The legs and thick, slightly decurved bill are greyish-horn in colour, accompanied by a yellowish-brown iris and a distinctive bare greenish-yellow eye-ring. Juveniles are distinguished by their more orange-buff upperparts and a noticeably paler lower mandible (Showler & Davidson, 1999).

The breeding period of Jerdon's Babbler appears to be synchronized with the monsoonal inundation of floodplains, though precise timing remains poorly documented. However, field vocal recordings and behavioural observations during the spring to early summer months (March–May) suggest that nesting activity likely coincides with the onset of the wet season in the region (Sadanandan et al., 2018).

This species is resident, insectivorous passerine, typically found in small groups or pairs within dense tall grasses and reeds (BirdLife International, 2021; Khan et al., 2014; Showler & Davidson, 1999). The vocalization based on the analysed recording of field recorded and data procured from xeno-canto conforms to established descriptions of the species' acoustic behaviour, characterized by a series of short, tonal, and rhythmically repeated notes resemble short "chak" or "chek" sounds. The dominant frequency peak at approximately 3500 Hz, along with concentrated energy between 2 - 12 kHz.

Classified as Vulnerable by IUCN (decline $\geq 30\%$ over three generations) with an estimated 2,500–9,999 mature individuals remaining (BirdLife International, 2021). Its decline stems from drainage of wetlands, agricultural conversion, dam construction (especially on Indus and Brahmaputra systems), grazing, and burning of habitats.

2.3 Ecology of Black-breasted Parrotbill

The (*Paradoxornis flavirostris*), first described scientifically by Gould, J., in 1836 with its type locality probably in Nepal, is a monotypic species within the genus *Paradoxornis*, family Paradoxornithidae. Its nomenclature reflects the yellow-billed beak (“*flavirostris*”), but it is distinguished by a large, parrot-like bill, a striking black throat and breast contrasting with warm rufous-buff underparts and brown upperparts (Marshall, 1972). Currently endemic to northeast India (Arunachal Pradesh and Assam), this species is confined to highly fragmented strongholds such as Manas and Dibru-Saikhowa National Parks, though historical data suggest past presence in Bangladesh and eastern Nepal (BirdLife International, 2024a; Grimmett et al., 2016; Marshall, 1972). Measuring approximately 19 cm in length, adults show distinctive plumage, black head-side patches and throat, uniform rufous-buff below, heavy bill, which aids in visual identification and differentiation from congeners (Choudhury, 2011; Penhallurick & Robson, 2009). Breeding biology remains poorly documented; Birds of the World notes a critical lack of recent nesting records, highlighting significant knowledge gaps regarding its phenology, clutch characteristics, and nesting ecology. The species inhabits dense reedbeds and tall grass stands dominated by *Phragmites karka* and *Arundo donax*, favoring wet grassland and marshy ecosystems subject to seasonal inundation (Bora & Saikia, 2024).

Ecologically, it is non-migratory, presumably granivorous-insectivorous, and often observed in small social groups a trait typical of parrotbills though detailed foraging studies are scarce. Vocal communication includes of a series of sharp, clear, and high-pitched notes that occur in rhythmic, repeated bursts, typically within the 1.2 to 3 kHz frequency range. These calls are often resembling a "phooi- phooi - phooi " pattern (Xeno-canto, 2025a). The Black-breasted Parrotbill is classified as Vulnerable (VU) on the IUCN Red List (IUCN 3.1). This designation is underpinned by a small and declining population, estimated at between approximately 1,500 and 7,000 mature individuals (BirdLife International, 2024a).

2.4 Ecology of Marsh Babbler

The Marsh Babbler (*Pellorneum palustre*), first described by Gould, in 1872, has its type specimen based on individuals from the Brahmaputra floodplain of northeast India and adjacent Bangladesh (Krishnan, 2021). This monotypic species, belonging to the ground-babbler family Pellorneidae, derives its specific epithet "*palustre*" from its marsh habitat, and is characterized by a modest 17 cm length, rich brown upperparts, paler buff underparts, a greyish throat, and the distinctive bare, flesh-toned facial skin around the eye (E. S. Baker, 1922). It is endemic to seasonally inundated tall grass and reedbeds dominated by *Phragmites* and associated marsh vegetation, within the Brahmaputra valley of Assam, Arunachal Pradesh, Meghalaya, and adjacent Bangladesh (Krishnan, 2021).

The nests are constructed low within dense reeds, typically from April to June coinciding with flood recession (Baker, 1932); clutches consist of approximately 3 - 4 eggs (Baker, 1922). Ecologically, it is a resident, skulking, ground-foraging insectivore and frequently observed in small family groups or pairs (Krishnan, 2021).

Its vocal repertoire is repetitive vocalization characterized by a series of short, whistling notes. The dominant frequency of the call averages around 3 kHz. The call predominantly occupies the 1–10 kHz frequency range. Acoustically, the call can be described as a rhythmic sequence of “Kekrrerere krorette- Kekrrerere krorette” phrases, often delivered in quick, uniform intervals (Xeno-canto, 2025b). The Marsh Babbler is assessed as Vulnerable (VU), primarily due to declining populations driven by habitat degradation and fragmentation in its floodplain ecosystems. Conservation actions focused on wetland protection and management are critical to its survival (BirdLife International, 2024c).

2.5 Habitat Requirements of Grassland Birds

Grassland ecosystems represent some of the most threatened habitats globally, with grassland-dependent bird species experiencing steeper population declines than any other avian guild (Brennan & Kuvlesky, 2005). Vegetation height emerges as one of the most critical habitat variables for grassland birds, with different species exhibiting distinct preferences along this structural gradient. Fuhlendorf et al. (2006) demonstrated that grass height significantly influences both foraging opportunities and predation risk for grassland

birds. Species-specific responses to vegetation height create a mosaic of microhabitat requirements within grassland ecosystems. Grassland birds require open, treeless landscapes with heterogeneous vegetation structure providing diverse microhabitat niches (Kraft et al., 2021). Research across North American, European, and Asian grassland systems consistently identifies key requirements including large patch sizes (Zuckerberg et al., 2018), appropriate disturbance regimes through fire and grazing maintaining optimal vegetation structure and preventing woody encroachment, and native plant communities dominated by native grasses supporting diverse arthropod food webs (Rosenberg et al., 2019).

Species-specific requirements create distinct ecological niches within grassland ecosystems. Short-grass specialists like the Upland Sandpiper (*Bartramia longicauda*) prefer vegetation heights of 5-20 cm and low vegetation density, enhancing visibility for predator detection and effective brood rearing (Griffis & Campa III, 2023). In contrast, tall-grass specialists such as Henslow's Sparrow (*Centronyx henslowii*) require denser vegetation 30-100 cm tall and significant litter accumulation (3-7 cm), which provide nesting cover and insulation (Keating et al., 2023). Generalist species like Bobolinks (*Dolichonyx oryzivorus*) occupy an intermediate niche, favoring mixed grass-forb assemblages with vegetation heights of 15 -50 cm and moderate litter cover (5 - 39%) (Shaffer et al., 2023).

Similarly, in India, the Paddyfield Pipit (*Anthus rufulus*), a non-migratory, insectivorous species, thrives in open grass-scrub mosaics and agricultural fields with short vegetation (10-20 cm), facilitating ground foraging (Nath et al., 2022). The Nilgiri Pipit (*Anthus nilghiriensis*), endemic to the montane grasslands of southern India, prefers short to medium grass heights (<25 cm) mixed with marshy patches and is most common in grasslands above 1900 m elevation (Lele et al., 2020). Species like the Painted Francolin (*Francolinus pictus*) favor semi-dry undulating grasslands with dense tall grasses and scrub, indicating a clear need for structurally complex tall-grass ecosystems (Forcina et al., 2012).

Research by With et al. (2008) revealed that many grassland bird species require heterogeneous vegetation structure rather than uniform grassland conditions. This heterogeneity provides diverse foraging opportunities and nesting sites while

accommodating different behavioural and ecological needs. The structural complexity of grasslands, including varying heights and densities, creates microhabitats that support different species assemblages (Derner et al., 2009).

The composition of plant communities significantly affects grassland bird habitat quality. Native grassland plant communities typically provide superior habitat compared to areas dominated by invasive species (Fletcher & Koford, 2002). Invasive plant species can alter habitat structure, reduce arthropod diversity, and modify seed availability, consequently affecting both foraging and nesting opportunities for grassland birds.

Studies by Scheiman et al. (2003) showed that areas with high invasive plant cover, particularly exotic grasses, supported lower bird diversity and abundance compared to native grassland areas. The structural and compositional changes associated with invasive species create suboptimal conditions for many specialist grassland birds, leading to reduced reproductive success and population viability.

2.5.1 Patch size and landscape context

Grassland bird communities are strongly influenced by patch size and landscape configuration. Herkert, (1994) established that many grassland bird species are area-sensitive, requiring large contiguous grassland patches for successful breeding. This area sensitivity varies among species, with some requiring patches exceeding 100 hectares for consistent occupancy.

The landscape context surrounding grassland patches also plays a crucial role in determining bird community composition. Ribic et al. (2009) found that the amount of grassland habitat within the surrounding landscape significantly influenced local bird communities, suggesting that both local and landscape-scale factors interact to determine habitat suitability.

Habitat fragmentation has emerged as a central driver of grassland bird declines, exerting profound effects on species composition, abundance, and persistence. Fragmentation not only reduces the total amount of available habitat but also alters its configuration, leading to increased edge effects and isolation. Studies across North America and Europe consistently demonstrate that bird species richness and occupancy are

positively correlated with fragment size and connectivity, with area-sensitive species requiring substantially larger patches for viable populations (Herse et al., 2020). Edge effects, often penetrating 100–800 meters into patches, diminish core habitat essential for nesting and foraging (Marcolin et al., 2021). Fragment isolation further limits dispersal, particularly when inter-patch distances exceed 700 meters, disrupting gene flow and metapopulation dynamics (Reino et al., 2013). While patch density and linear corridors can mitigate some fragmentation impacts, the surrounding agricultural matrix often presents low-quality habitat that hampers movement (Buxton & Benson, 2016). These findings underscore the urgent need for landscape-scale conservation strategies that maintain large, connected, and minimally perforated grassland systems.

2.5.2 Climate variables

Climate variables, particularly temperature and precipitation patterns, influence grassland bird distributions through both direct physiological effects and indirect effects on habitat quality. McCarty and Winkler (1999) demonstrated that breeding phenology in grassland birds is closely tied to temperature patterns, with earlier warming leading to advances in breeding timing.

Precipitation patterns affect grassland productivity, vegetation structure, and arthropod abundance, all of which influence grassland bird communities (Skagen et al., 2018). Years with optimal precipitation timing and amounts typically support higher bird densities and breeding success rates compared to drought or flood years. Local microclimate conditions within grassland habitats can significantly influence bird habitat selection and breeding success. Wind exposure, humidity levels, and temperature variations within grassland patches create microhabitat gradients that different species exploit differentially (Bakker et al., 2002). Cloud cover and its effects on temperature regulation and foraging conditions have been identified as important factors for some grassland bird species, particularly those that rely on visual foraging strategies (Pietz & Granfors, 2000).

2.5.3 Soil characteristics

Soil characteristics indirectly influence grassland bird communities through their effects on plant community composition and arthropod abundance. Soil pH affects plant

species composition, which in turn influences the structural characteristics of grassland habitats (Gibson et al., 1993).

Research by Dennis et al. (1998) showed that soil fertility levels affect both plant diversity and arthropod communities, with implications for grassland bird foraging opportunities. Soils with moderate fertility levels often support the most diverse plant and arthropod communities, providing optimal foraging conditions for insectivorous grassland birds.

Soil temperature and moisture regimes influence both plant growth patterns and invertebrate communities that serve as food sources for grassland birds. These soil characteristics create spatial and temporal variations in resource availability that affect bird distribution and abundance patterns (Knapp et al., 1998). The interaction between soil characteristics and climate variables creates complex patterns of habitat suitability that vary both spatially and temporally, requiring adaptive management approaches for grassland bird conservation (Samson & Knopf, 1994).

2.5.4 Water availability and wetland proximity

Water availability, either through permanent water sources or seasonal wetlands, influences grassland bird distribution and abundance. Many grassland bird species require access to water for drinking and foraging, particularly during hot, dry periods (Rotenberry & Wiens, 1991). The proximity of wetland habitats to grasslands creates ecotonal zones that support unique bird communities and provide additional foraging opportunities for some grassland species (Fairbairn & Dinsmore, 2001).

2.6 Conservation Status and Threats

Grassland birds represent one of the most imperilled avian guilds globally, with populations experiencing precipitous declines that exceed those of any other bird group (Rosenberg et al., 2016). The conservation crisis facing grassland-dependent species is particularly acute in Asia, where rapid economic development, agricultural intensification, and habitat conversion have dramatically altered traditional grassland ecosystems (BirdLife, 2018).

2.6.1 Global conservation status of grassland birds

Continental-scale analyses reveal that grassland birds have experienced the steepest population declines of any avian habitat guild over the past several decades. Rosenberg et al. (2019) documented more than 50% decline in grassland bird populations across North America since 1970, representing a loss of approximately 720 million individual birds (Sauer, Niven, et al., 2017). Similar patterns have been documented across other continents, with European grassland birds showing comparable decline rates (Donald et al., 2001).

Asian grassland bird populations face particularly severe conservation challenges due to rapid economic development and intensive land-use changes. Robson (2020) documented significant population declines among grassland-dependent species across East Asia, with habitat loss identified as the primary driver. The situation is particularly critical in regions like the Brahmaputra basin, where traditional grassland management practices have been disrupted by modern development pressures (Sharma et al., 2023).

Studies by Robson (2020) in Southeast Asia revealed that many grassland bird species have experienced range contractions of 50% or more over the past century. Endemic and range-restricted species face the highest extinction risks, as their limited distributions make them particularly vulnerable to localized threats.

2.6.2 Habitat loss and conversion

Habitat loss represents the most significant threat to grassland birds globally. Agricultural intensification, urbanization, and infrastructure development have resulted in widespread conversion of natural grasslands to other land uses (Samson et al., 2004). In Asia, rapid economic development has accelerated grassland conversion rates, with some regions losing over 80% of their natural grassland cover within a few decades (Kamp et al., 2016).

The conversion of grasslands to intensive agriculture eliminates habitat for specialist grassland birds while creating simplified landscapes that support fewer species overall. Fletcher and Koford (2003) demonstrated that even partial conversion of grassland landscapes significantly reduces bird diversity and abundance.

2.6.3 Agricultural intensification

Modern agricultural practices pose multiple threats to grassland birds, including increased pesticide use, earlier and more frequent mowing, and conversion from extensive to intensive production systems. Donald et al. (2001) identified agricultural intensification as the primary driver of grassland bird declines across Europe, with similar patterns documented in other regions.

Pesticide use directly affects grassland birds through reduced invertebrate prey availability and potential direct toxicity effects. Mineau and Whiteside (2013) found that neonicotinoid pesticides, widely used in modern agriculture, significantly reduce arthropod abundance in grassland systems, consequently affecting insectivorous birds.

Agricultural intensification represents one of the primary threats to grassland bird populations globally. Brennan and Kuvlesky (2005) documented severe population declines in grassland birds associated with changes in agricultural practices, including increased use of pesticides, earlier and more frequent mowing, and conversion of grasslands to row crops.

The timing and intensity of agricultural activities significantly affect grassland bird breeding success. Perlut et al. (2006) found that delayed mowing schedules improved nest success rates for several grassland bird species, highlighting the importance of timing in agricultural management practices.

2.6.4 Infrastructure development and fragmentation

Transportation infrastructure, energy development, and urban expansion fragment grassland habitats and introduce various disturbance factors that negatively affect bird populations. Bayne et al. (2008) documented that roads reduce habitat quality for grassland birds through direct mortality, noise pollution, and edge effects that extend hundreds of meters into adjacent habitats.

Wind energy development, while beneficial for climate change mitigation, poses specific challenges for grassland birds through direct mortality from turbine strikes and habitat displacement effects. Loss et al. (2013) estimated that wind turbines kill lakhs of birds annually in the United States, with grassland species being disproportionately affected.

Power line networks create additional mortality sources through electrocution and collision, while also fragmenting grassland habitats. Bernardino et al. (2018) found that power lines cause significant mortality in grassland birds, particularly during migration periods when birds may be less familiar with local hazards. Edge effects significantly influence grassland bird communities, with many species avoiding habitat edges due to increased predation pressure and altered microclimate conditions. Johnson and Temple (1990) found that nest predation rates were significantly higher near grassland edges compared to interior areas.

Mining activities pose particular threats to grassland ecosystems through direct habitat destruction, water pollution, and long-term landscape alteration. Northrup and Wittemyer (2013) found that energy development significantly reduces habitat quality for grassland birds even when direct habitat loss is minimal.

The width and composition of edge zones affect their impact on grassland bird communities. Soft edges, created by gradual transitions between habitat types, generally have less severe effects than hard edges created by abrupt habitat changes (Ries et al., 2004).

2.6.5 Climate change

Climate change poses both direct and indirect threats to grassland birds through altered temperature and precipitation patterns, shifting vegetation communities, and changes in extreme weather frequency (Şekercioğlu et al., 2012). Langham et al. (2015) projected that 64% of North American grassland bird species face significant climate-related threats, with many species requiring shifts in their geographic ranges to track suitable climate conditions.

Changing precipitation patterns affect grassland productivity and structure, potentially altering habitat suitability for different species. Langham et al. (2015) found that drought conditions significantly reduce grassland bird reproductive success and survival rates, while extreme precipitation events can cause direct mortality and habitat degradation.

Temperature increases may affect grassland birds through multiple pathways, including altered prey availability, increased heat stress, and mismatches between breeding

timing and optimal resource availability (Both, 2010). McKechnie and Wolf (2010) identified several grassland bird species as particularly vulnerable to temperature increases due to their limited thermoregulatory capacity.

2.6.6 Invasive species

Invasive plant and animal species pose significant threats to grassland bird communities by altering habitat structure, reducing native plant diversity, and introducing novel predation or competition pressures (Saalfeld et al., 2016). DiTomaso (2000) documented that invasive grasses fundamentally alter grassland fire regimes and vegetation structure, creating suboptimal conditions for many native bird species.

Invasive predators can have devastating effects on grassland bird populations, particularly on islands or in regions where native predator communities have been disrupted (Hilton & Cuthbert, 2010). Blackburn et al. (2004) showed that introduced predators cause significantly higher nest failure rates compared to native predator species. The interaction between invasive species and other threats can create synergistic effects that exceed the sum of individual impacts (Doherty et al., 2015). Brooks et al. (2004) found that invasive species establishment is often facilitated by habitat disturbance from other sources, creating cascading effects on native bird communities.

2.6.7 Fire regime alterations

Natural fire regimes have historically maintained grassland ecosystems, but fire suppression and altered burning patterns now threaten grassland bird habitat quality. Fuhlendorf and Engle (2004) demonstrated that fire suppression leads to woody encroachment and loss of grassland habitat, while inappropriate burning regimes can eliminate critical nesting cover during breeding seasons. Research by Robbins and Dale (1999) showed that moderate disturbance regimes often support the highest grassland bird diversity, while either complete disturbance absence or intensive disturbance reduces habitat suitability for many species. The timing, frequency, and intensity of prescribed burns significantly affect grassland bird communities. Robbins and Dale (1999) found that annual burning creates suboptimal conditions for many grassland species, while fire exclusion leads to habitat degradation through woody invasion.

Climate change may further alter fire regimes through increased frequency of extreme weather events and altered vegetation moisture conditions. Flannigan et al. (2013) projected significant increases in fire frequency and intensity across many grassland regions, potentially exceeding the adaptive capacity of some bird species.

2.6.8 Pollution and contamination

Chemical pollution affects grassland birds through multiple pathways, including direct toxicity, endocrine disruption, and indirect effects through prey population impacts (Dudgeon, 2000). Mineau (2003) documented that agricultural pesticides cause both lethal and sublethal effects in grassland birds, with impacts on reproduction, behaviour, and immune function.

Plastic pollution represents an emerging threat to grassland birds, particularly species that forage in agricultural landscapes where plastic debris is common. Wilcox et al. (2015) found plastic ingestion in multiple grassland bird species, with potential impacts on nutrition and reproductive success.

2.6.9 Traditional land use changes

Changes in traditional land management practices threaten grassland birds that have co-evolved with extensive grazing and burning regimes. In many Asian regions, abandonment of traditional pastoralism has led to habitat degradation through woody encroachment or conversion to intensive agriculture (Kamp et al., 2016). The loss of traditional ecological knowledge associated with sustainable grassland management compounds these challenges. Drew and Henne (2006) emphasized that grassland conservation requires integration of traditional management practices with modern conservation approaches.

2.6.10 Water resource development

Large-scale water resource development projects, including dam construction and river diversions, significantly affect grassland birds through altered flooding regimes and wetland loss (Dudgeon, 2000). Nilsson et al. (2005) documented that dam construction has altered 60% of the world's rivers, with particularly severe impacts on floodplain grassland ecosystems.

The Brahmaputra River system faces multiple water development pressures that threaten the grassland bird communities dependent on natural flooding cycles. Goswami et al. (1999) found that proposed hydroelectric developments could significantly alter downstream grassland habitats critical for vulnerable species. The temporal sequence of threats can also affect their cumulative impact. Species that have already experienced population declines due to habitat loss may be less resilient to additional stressors like climate change or pollution (Didham et al., 2007).

2.7 Species Distribution Modelling in Avian Conservation

2.7.1 Ensemble modelling approaches

Species distribution modelling has advanced significantly with ensemble modelling approaches demonstrating superior performance over single algorithms when properly tuned across different species globally (Hao et al., 2020). Recent developments show both performance-based and diversity-based ensemble selection strategies prove effective, with heterogeneous ensembles consistently outperforming single models across bird species datasets. However, ensembles built using Biomod framework with default parameters performed no better than moderate single models, emphasizing the critical importance of proper parameter tuning (Hao et al., 2019).

MaxEnt modelling remains among top-performing algorithms, particularly effective for presence-only data with small sample sizes (Valavi et al., 2022). Enhanced parameterization through empirical tuning using presence-only data improves model accuracy and computational efficiency, with recent implementations incorporating "hinge features" for modelling complex relationships and logistic output formats providing probability estimates (Merow et al., 2013). Bias correction methods through background sampling strategies address sample selection bias while reducing model-building time (Phillips et al., 2009).

2.7.2 Machine learning techniques

Random Forest and other machine learning techniques show strong potential when properly implemented (Ao et al., 2019). Random Forest with default parameters performs poorly for presence-background modelling, but optimized parameters addressing class

imbalance significantly improve performance, producing strong models (Valavi et al., 2021). Geographically Weighted Random Forest incorporates spatial heterogeneity by focusing on local rather than global calculations, particularly suitable for applications with complex spatial structures (Georganos et al., 2021). XGBoost emerges as a powerful alternative showing strong performance in comparative studies (Demir & Sahin, 2023).

2.7.3 Bioclimatic variables and remote sensing

Variable selection significantly affects model outcomes, with using all available bioclimatic variables versus tailored selection creating substantial differences in predictions. Over-fitting with numerous variables can lead to overestimated range reduction predictions, while different databases using varying calculation methods for bioclimatic variables make results incomparable. Bede-Fazekas and Somodi (2020); and Durán et al. (2020) demonstrated that different calculation schemes can project both large increases and decreases for the same habitats.

Chapter 3

CHAPTER 3

ASSESSMENT OF HABITAT CHARACTERISTICS

This chapter addresses the first objective of the thesis, which is “*To assess the habitat characteristics of three select threatened grassland birds namely Jerdon’s Babbler, Black-breasted Parrotbill and Marsh Babbler*”.

3.1 Introduction

The assessment of habitat characteristics forms the cornerstone of effective conservation strategies, particularly for threatened species whose survival depends on specific environmental conditions and resource availability (Hairston et al., 1960). In the context of Northeast India's Brahmaputra floodplains, understanding the habitat requirements of threatened grassland birds becomes increasingly critical as these ecosystems face unprecedented anthropogenic pressures and climate-induced changes.

The three focal species of this study Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*) represent indicator species for grassland conservation in the region. These species have experienced significant population declines and range contractions, making them ideal indicators of ecosystem health and habitat quality (BirdLife International, 2025). Their conservation status underscores the urgent need for comprehensive habitat characterization to inform evidence-based management decisions.

Recent advances in habitat modelling have revealed that successful conservation requires understanding not just the presence of suitable habitat, but the quality and connectivity of these habitats across landscapes (Savary et al., 2024). The integration of call playback techniques with habitat assessment provides additional insights into species detection probabilities and territorial behaviours, crucial for accurate population estimates and habitat quality assessments (Barrero et al., 2024). Vegetation structure parameters, including grass height, cover percentage, and species composition, have consistently emerged as primary determinants of grassland bird community structure (Jahan et al., 2022b; Skowno & Bond, 2003).

3.1.1 Chapter objectives and structure

This chapter presents a comprehensive assessment of habitat characteristics associated with Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler in the Brahmaputra floodplains. By quantifying the habitat characteristics that determine the presence and abundance of these threatened grassland birds, this research contributes essential baseline data for conservation planning.

3.2 Methods

This study employed an integrated multi-scale approach combining extensive field surveys, remote sensing analysis, and statistical modelling to assess the habitat characteristics, and distribution patterns, of three select threatened grassland bird species in the Brahmaputra River system across Assam and Arunachal Pradesh, encompassing the historical range of all three target species. Field data collection was conducted during two separate seasons in 2018 and 2020, employing standardized point-count surveys and species-specific call playback techniques across 756 systematically selected survey sites. These field observations were complemented by high-resolution remote sensing data from Sentinel-1 and Sentinel-2 satellites, providing comprehensive habitat characterization at multiple spatial scales.

Environmental variables were derived from multiple sources, including field measurements of vegetation structure, satellite-based spectral indices, topographic derivatives, and anthropogenic disturbance indicators. This multi-dimensional environmental dataset encompassed landscape ecological metrics, vegetation productivity indices, climatic variables, and human impact measures, to capture the complex habitat requirements of these specialized grassland species.

3.2.1 Data analysis framework

The analytical framework for assessing habitat characteristics and requirements of the three threatened grassland birds (Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler) employed a multi-step approach combining statistical methods with machine learning techniques. This methodology was consistently applied across all three species to ensure comparability and robustness of results. The analytical pipeline encompassed data preprocessing, exploratory data analysis, variable transformation,

correlation analysis, dimensionality reduction, and predictive modelling using both generalized linear models (GLMs) and random forest algorithms.

3.2.2 Variable selection and ecological justification

Landscape Ecological Metrics were employed to quantify habitat heterogeneity and spatial configuration patterns critical for grassland bird species survival. Shannon diversity and Simpson diversity indices were measured habitat heterogeneity levels, as different grassland specialists may prefer varying degrees of landscape diversity versus homogeneous grasslands. Class richness indicated landscape complexity influencing species occurrence patterns, while edge density assessed edge effects between habitats, some species prefer edges while others, particularly grassland specialists, avoid them. Patch coherence measured landscape connectivity, critical for species with limited dispersal ability, and dominance and evenness indices evaluated species tolerance to landscape heterogeneity, helping identify preferences for uniform versus mixed landscapes.

Remote Sensing Vegetation Indices served as primary indicators of vegetation productivity, health, and structural characteristics essential for habitat quality assessment. NDVI functioned as the primary vegetation productivity indicator relating to food availability, nesting sites, and overall habitat quality, while NDCI indicated plant health and photosynthetic activity as habitat quality proxies. EVI provided improved vegetation assessment in dense canopy areas with reduced atmospheric interference, and SAVI accounted for soil background effects important in sparse grassland areas. GNDVI measured chlorophyll content variations indicating seasonal vegetation changes, while NDWI and NDMI assessed water and moisture content in vegetation, critical for grassland species requiring moist conditions. Additional indices including moisture stress index, fractional vegetation cover, bare soil index, and grass senescence index provided comprehensive vegetation structure and temporal dynamics assessment.

Topographic Variables characterized microclimatic conditions and drainage patterns significantly influencing habitat suitability. Elevation controlled microclimatic conditions, drainage patterns, and vegetation composition, with many grassland birds showing specific elevation preferences. Slope influenced drainage, soil development, and vegetation structure affecting habitat suitability and accessibility, while aspect determined solar exposure affecting microclimate, vegetation growth patterns, and insect abundance.

The Topographic Wetness Index (TWI) predicted soil moisture patterns critical for wetland grassland species, and terrain roughness influenced accessibility, predator-prey dynamics, and vegetation establishment patterns.

Climate and Environmental Variables provided essential environmental context for species habitat requirements. Land Surface Temperature (LST) median affected species metabolism, breeding timing, and food availability, while water occurrence frequency proved critical for species requiring proximity to water sources for drinking, bathing, and accessing aquatic food resources, particularly important for the three target species known to inhabit riverine grasslands.

Spatial Distance Variables quantified proximity effects and edge influences from various habitat types and anthropogenic features. Distance to water bodies measured proximity to essential water sources, while distances to agricultural land, woodland, and scrubland assessed edge effects and habitat transition zones that may provide resources or represent habitat degradation. Specific distances to key grass species including *Phragmites*, *Vetiver*, and *Saccharum* were measured as these represent critical habitat components for the target species. Distance to built-up areas quantified anthropogenic disturbance levels, and distance to riverine deposits indicated dynamic floodplain processes affecting habitat availability.

Field-Measured Vegetation Structure provided ground-truth data on specific habitat requirements. Overall grass height directly affected nesting sites, predator visibility, and microhabitat structure, while grass coverage influenced accessibility, food resources, and nesting opportunities. Species-specific measurements including *Saccharum*, *Erianthus*, *Vetiveria*, and *Phragmites* heights and coverage were critical as these grass types provide specific microhabitat conditions required by threatened grassland specialists, with *Phragmites* being particularly essential for reed-dependent species habitat assessment.

Anthropogenic Disturbance Variables quantified human impact intensity on habitat quality and species survival. Resource extraction activities measured direct habitat destruction and disturbance intensity, while livestock grazing pressure significantly altered vegetation structure, composition, and habitat quality. Fire frequency and intensity affected vegetation regeneration, structure, and species composition, and mining activity represented severe habitat degradation with long-term ecosystem disruption potential, all factors directly threatening the persistence of the three target grassland bird species in the Brahmaputra floodplains.

3.2.3 Data preprocessing and quality control

Prior to analysis, comprehensive data quality assessment and preprocessing were conducted following established protocols in ecological data analysis (Khosravi et al., 2019; Rather et al., 2020). Variables with more than 50% missing values were excluded from the analysis to maintain data integrity and prevent biased parameter estimates. For remaining variables with less than 50% missing data, median imputation was employed for continuous variables, while mode imputation was used for categorical variables, following established practices in ecological modelling (Valavi et al., 2022).

Outlier detection and treatment were performed using multiple approaches to identify potentially erroneous data points that could unduly influence model performance. The detection process involved examining univariate distributions through histograms and boxplots, combined with multivariate outlier detection using Mahalanobis distance calculations. This comprehensive approach ensured that both univariate and multivariate outliers were identified and appropriately handled (Rather et al., 2020). Following outlier identification, data points were carefully evaluated for ecological plausibility before removal, ensuring that legitimate extreme values representing natural ecological variation were retained in the dataset.

3.2.4 Correlation analysis and multicollinearity assessment

Comprehensive correlation analysis was conducted to identify relationships among predictor variables and assess multicollinearity (Figure 5), which can significantly impact model performance and interpretation. The analysis employed Pearson correlation coefficients to quantify linear relationships between continuous variables (Table 2), with correlation matrices visualized using the *corrplot* package in R (Rather et al., 2020). Variables exhibiting high correlation coefficients ($|r| > 0.8$) were flagged for potential multicollinearity issues, following established thresholds in ecological modelling (Rahayu et al., 2017).

3.2.5 Principal component analysis

Principal Component Analysis (PCA) was employed as a dimensionality reduction technique to identify the most important patterns of variation in the environmental data and address multicollinearity issues (Figure 6) among predictor variables (Cruz-Cárdenas et al., 2014).

The number of principal components to retain was determined using multiple criteria, including the scree plot method, Kaiser's criterion (eigenvalues > 1), and the cumulative proportion of variance explained.

Table 2 Selected Variables for the analysis

DIMENSION	VARIABLES	WHY IMPORTANT
HABITAT DIVERSITY	Shannon Diversity	The study species is vulnerable to habitat heterogeneity
VEGETATION HEALTH	NDVI, EVI, NDMI	Primary productivity and moisture availability
SPATIAL CONTEXT	Elevation	Climate and topographic gradients
LANDSCAPE	Distance variables	Connectivity and edge effects
MICROHABITAT	Grass heigh, Cover	Nesting and foraging structure
DISTURBANCE	Grazing, Fire	Management impacts on habitat

3.2.6 Generalized linear models

Generalized Linear Models (GLMs) were implemented to model the relationship between species presence/absence and environmental predictor variables, accounting for the binomial distribution of the response variable. For presence/absence data, logistic regression models were fitted using the binomial family with logit link function, which is appropriate for binary response variables (Nelder & Wedderburn, 1972). The logistic regression model was formulated as:

$$\text{logit}(\pi) = \log(\pi/(1 - \pi)) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p$$

where π represents the probability of species presence, and β coefficients represent the log-odds ratios associated with each predictor variable. This approach is particularly suitable for ecological modelling as it constrains predicted probabilities between 0 and 1, which is biologically meaningful for presence/absence data (Nelder & Wedderburn, 1972)

3.2.7 Random Forest Analysis

Random Forest analysis was implemented as a non-parametric machine learning approach to model species-habitat relationships and assess variable importance (Rather et al., 2020). Random Forest is particularly well-suited for ecological data as it can handle non-linear relationships, interaction effects, and mixed data types without requiring assumptions about data distribution (Evans et al., 2011). The algorithm constructs multiple decision trees using bootstrap sampling and random feature selection, with final predictions based on majority voting (for classification) or averaging (for regression) across all trees.

The Random Forest models were implemented using the `randomForest` package in R, with 500 trees developed to ensure model stability and convergence. The number of variables randomly sampled at each split (`mtry` parameter) was optimized using out-of-bag (OOB) error rates, typically set to the square root of the total number of predictor variables for classification problems (Magness et al., 2008). Class weights were balanced to address potential issues with unequal sample sizes between presence and absence observations. Variable importance was assessed using two metrics: mean decrease in accuracy and mean decrease in Gini impurity.

3.3 Results

3.3.1 Habitat characteristics and distribution patterns of Jerdon's Babbler

During the survey, we could identify Jerdon's Babbler populations at multiple locations within the species' fragmented range. The detection success using point-count and call playback methodologies proved effective for this shy and skulking species.

3.3.2 Habitat associations and environmental variables

3.3.2.1 Generalized Linear Model

The GLM analysis revealed highly distinctive and specialized habitat associations for Jerdon's Babbler presence. Among the 20 predictor variables examined, several showed exceptionally strong statistical relationships with species occurrence.

Table 3 Generalized Linear Model Results of Jerdon's Babbler

Predictor	Estimate	Std. Error	z	p-value	
(Intercept)	-8.756	3.745	-2.34	0.019	*
elevation	0.011	0.003	3.16	0.002	**
Shannon Diversity	-0.418	0.393	-1.06	0.287	
NDVI	-2.473	1.306	-1.89	0.058	.
NDMI	4.664	1.702	2.74	0.006	**
TWI	-0.058	0.410	-0.14	0.887	
Land Surface Temperature	0.047	0.059	0.80	0.424	
Water Occurrence	-0.007	0.014	-0.55	0.586	
dist_to_WaterBodies	0.084	0.111	0.76	0.448	
dist_to_BuiltUp	0.179	0.151	1.18	0.237	
dist_to_Vetiver	-0.176	0.095	-1.87	0.062	.
dist_to_Pragmites	-0.227	0.109	-2.08	0.038	*
dist_to_Woodland	-0.019	0.153	-0.12	0.902	
dist_to_Saccharum	-0.389	0.082	-4.73	< 0.001	***
Saccharum Hight	0.314	0.033	9.64	< 0.001	***
Vetiveria Hight	0.185	0.035	5.26	< 0.001	***
Phragmites Hight	0.073	0.030	2.40	0.016	*
Grazing	-0.369	0.072	-5.13	< 0.001	***
Fire	-0.312	0.080	-3.91	< 0.001	***
Extraction	-1.400	111.682	-0.01	0.990	
Grass Senescence Index	3.435	2.443	1.41	0.160	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

3.3.2.1.1 Vegetation Structure Variables

Saccharum grasslands emerged as the highest habitat preference, with *Saccharum* Height showing the strongest positive association ($\beta = 0.314$, $z = 9.64$, $p < 0.001$). Additionally, the highly significant negative relationship with *dist_to_Saccharum* ($\beta = -0.389$, $z = -4.73$, $p < 0.001$) reinforces the species' absolute dependence on proximity to *Saccharum* *sp.* patches.

Vetiveria Height also demonstrated a highly significant positive association ($\beta = 0.185$, $z = 5.26$, $p < 0.001$), while *Phragmites* Height showed a moderate positive relationship ($\beta = 0.073$, $z = 2.40$, $p = 0.016$).

Elevation showed a significant positive association ($\beta = 0.011$, $z = 3.16$, $p = 0.002$), indicating preference for low land grass within the floodplain. This preference likely reflects microhabitat selection within the broader floodplain ecosystem that supports the dense, contiguous grassland stands the species requires.

NDMI displayed a highly significant positive relationship ($\beta = 4.664$, $z = 2.74$, $p = 0.006$), reflecting the species' requirement for moist grassland conditions. Interestingly, NDVI showed a marginally significant negative association ($\beta = -2.473$, $z = -1.89$, $p = 0.058$), suggesting preference for specific vegetation productivity levels rather than maximum greenness.

The species showed a significant negative association with *dist_to_Pragmites* ($\beta = -0.227$, $z = -2.08$, $p = 0.038$) and marginally significant negative relationship with *dist_to_Vetiver* ($\beta = -0.176$, $z = -1.87$, $p = 0.062$), indicating preferences for proximity to diverse tall grass types within the grassland matrix.

3.3.2.1.2 Anthropogenic Impact Variables

Grazing showed one of the strongest negative associations ($\beta = -0.369$, $z = -5.13$, $p < 0.001$), consistent with the species' documented preference for dense, contiguous, undisturbed stands of grass and general avoidance of disturbed habitats. Fire impact demonstrated similarly strong negative effects ($\beta = -0.312$, $z = -3.91$, $p < 0.001$).

3.3.2.2 Variable Importance of Random Forest

The Random Forest analysis provided insights into habitat variable importance, revealing an hierarchy of environmental drivers (Table 4).

Table 4 Random Forest Variable Importance for Presence of Jerdon's Babbler

Predictor	Mean Decrease Accuracy	Mean Decrease Gini
Saccharum Height	49.43	41.70
Elevation	33.13	25.04
dist_to_Saccharum	23.88	16.03
NDVI	16.34	12.58
dist_to_Woodland	16.69	12.05
NDMI	9.49	11.70
dist_to_WaterBodies	10.97	10.82
Vetiveria Height	17.42	10.61
Land Surface Temperature	12.62	9.72
dist_to_Pragmites	11.57	8.86
Grass_Senescence_Index	7.73	8.59
dist_to_BuiltUp	5.11	7.56
Grazing	15.01	7.37
dist_to_Vetiver_log	8.61	6.92
Water Occurrence	10.18	6.75
TWI	3.82	6.42
Phragmites Height	11.37	3.93
Shannon Diversity	4.82	3.70
Fire	8.60	3.17
Extraction	1.42	0.01

Note. Higher values indicate greater importance. Gini importance reflects variable contribution to node purity.

Saccharum Height emerged as by far the most important variable (Mean Decrease Accuracy = 49.43, Mean Decrease Gini = 41.70), showing nearly 50% higher importance than the second-ranked variable.

Elevation ranked second in importance (Mean Decrease Accuracy = 33.13, Mean Decrease Gini = 25.04), followed by dist_to_Saccharum (Mean Decrease Accuracy = 23.88, Mean Decrease Gini = 16.03), further emphasizing the critical importance of spatial proximity to *Saccharum* patches. The prominence of Vetiveria Height (Mean Decrease Accuracy = 17.42, Mean Decrease Gini = 10.61) and distance to woodland variables reflects the species' preference for specific grassland configurations within the floodplain mosaic.

Grazing showed high importance (Mean Decrease Accuracy = 15.01, Mean Decrease Gini = 7.37), while fire ranked lower but still significant (Mean Decrease Accuracy = 8.60, Mean Decrease Gini = 3.17), confirming the critical negative impacts of these disturbances on species occurrence patterns.

3.3.2.3 Model performance and validation

The GLM diagnostics for Jerdon's Babbler presence data revealed excellent model performance with appropriate residual patterns (Figure 7). The residuals vs. fitted values plot demonstrated good model specification with no obvious systematic deviations. The Q-Q plot showed reasonable adherence to normality assumptions, while the Scale-Location plot indicated stable variance across the prediction range. The residuals vs. leverage plot identified no influential outliers, suggesting robust model estimation.

3.3.2.4 Spatial distribution patterns

The spatial analysis revealed that Jerdon's Babbler distribution pattern characterized by clustered patch occurrence (Figure 8). The species shows distribution in pockets of the Brahmaputra grassland system, with highest abundances occurring in discrete locations primarily in the middle (Around Kaziranga grassland island regions), upper portion of Brahmaputra in Assam and Isolated Brahmaputra Grasslands of Arunachal Pradesh.

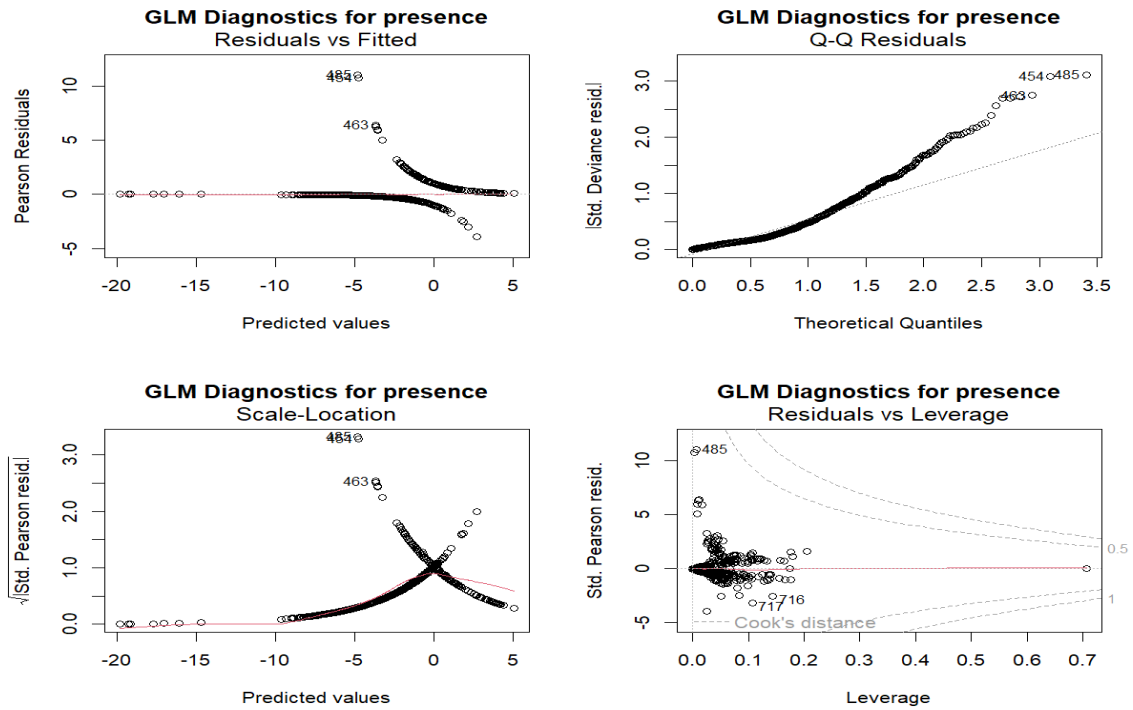


Figure 7 Model diagnostic plots for GLM predicting the presence probability of Jerdon's Babbler

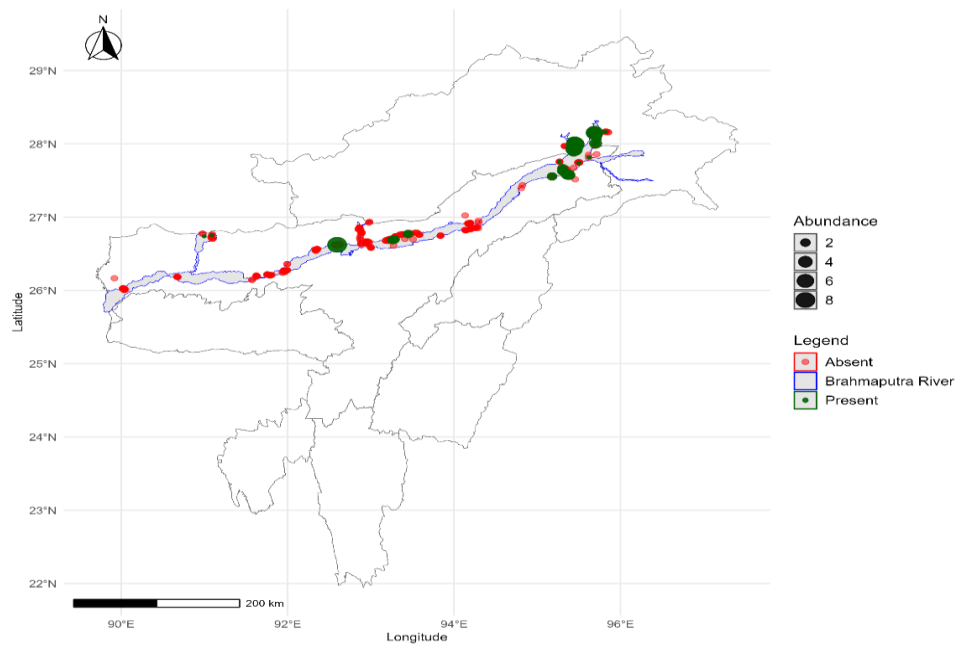


Figure 8 Spatial distribution of Jerdon's Babbler presence and sampling sites along the study area.

3.3.3 Habitat characteristics and distribution patterns of Black-breasted Parrotbill (*Paradoxornis flavirostris*)

3.3.3.1 Generalized Linear Model

The GLM analysis revealed high and statistically robust habitat associations for Black-breasted Parrotbill presence, demonstrating the species complex ecological requirements within the Brahmaputra floodplain ecosystem (Table 5).

Elevation emerged as one of the strongest positive predictors ($\beta = 0.016$, $z = 4.55$, $p < 0.001$), indicating preference for elevated microsites within the floodplain landscape. The species demonstrated the strongest negative association with dist_to_Pragmites ($\beta = -0.455$, $z = -5.06$, $p < 0.001$), indicating an absolute requirement for proximity to *Phragmites* stands. The highly significant negative relationship with dist_to_Vetiver ($\beta = -0.352$, $z = -3.68$, $p < 0.001$) further emphasizes the species' dependence on diverse tall grass assemblages within close spatial proximity.

Table 5 GLM Results for Presence of Black-breasted Parrotbill

Predictor	Estimate	Std. Error	z	p-value	
(Intercept)	-8.856	3.455	-2.56	0.010	*
elevation	0.016	0.004	4.55	< 0.001	***
shannon_diversity	-0.127	0.434	-0.29	0.770	
NDVI	-2.724	1.117	-2.44	0.015	*
NDMI	1.878	1.627	1.15	0.248	
TWI_log	0.445	0.388	1.15	0.251	
LST	0.091	0.062	1.48	0.140	
waterOccurrence	0.009	0.013	0.68	0.498	
dist_to_WaterBodies_log	-0.210	0.112	-1.88	0.061	.
dist_to_BuiltUp_log	-0.075	0.155	-0.49	0.626	
dist_to_Vetiver_log	-0.352	0.096	-3.68	< 0.001	***
dist_to_Pragmites_log	-0.455	0.090	-5.06	< 0.001	***

Predictor	Estimate	Std. Error	z	p-value	
dist_to_Woodland_log	0.671	0.192	3.49	< 0.001	***
saccharumHight_sqrt	0.045	0.031	1.45	0.148	
VetiveriaHight_sqrt	0.136	0.031	4.42	< 0.001	***
PhragmitesHight_sqrt	-0.008	0.032	-0.24	0.810	
grazing_sqrt	-0.078	0.069	-1.14	0.254	
fire_sqrt	-0.190	0.098	-1.94	0.052	.
extracn_sqrt	-1.596	124.411	-0.01	0.990	
Grass_Senescence_Index	0.692	2.440	0.28	0.777	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

A particularly notable finding was the strong positive relationship with dist_to_Woodland ($\beta = 0.671$, $z = 3.49$, $p < 0.001$), indicating that Black-breasted Parrotbill actively avoids proximity to wooded areas. This suggests the species requires open grassland configurations and may be negatively affected by landscape heterogeneity that includes woody vegetation. This finding has important implications for habitat management and restoration planning.

Surprisingly, NDVI demonstrated a significant negative association ($\beta = -2.724$, $z = -2.44$, $p = 0.015$), suggesting the species may prefer grasslands with specific vegetation characteristics rather than maximum productivity. This pattern could indicate preference for mature grassland communities or specific phenological stages that optimize foraging opportunities and nesting habitat quality.

Distance to water bodies showed a marginally significant negative relationship ($\beta = -0.210$, $z = -1.88$, $p = 0.061$), indicating preference for proximity to water sources, consistent with the species' wetland habitat requirements for dense reed thickets and mixed tall grasslands. Fire impact demonstrated a marginally significant negative association ($\beta = -0.190$, $z = -1.94$, $p = 0.052$).

3.3.3.2 Variable Importance of Random Forest

The Random Forest analysis provided clarity regarding habitat variable importance, revealing a distinct hierarchy of environmental drivers that differed markedly from traditional single-variable approaches (Table 6). Machine learning methods have proven superior for capturing complex ecological relationships in threatened grassland species (Evans et al., 2011; Cushman et al., 2020).

Table 6 Random Forest Variable Importance for Presence of Black-breasted Parrotbill

Predictor	Mean Decrease Accuracy	Mean Decrease Gini
dist_to_Pragmites_log	23.61	11.65
elevation	20.11	11.08
NDMI	11.15	9.35
dist_to_BuiltUp_log	7.19	8.84
VetiveriaHight_sqrt	12.31	8.81
NDVI	14.57	8.74
dist_to_Woodland_log	13.31	8.30
dist_to_WaterBodies_log	7.25	7.79
LST	9.29	7.60
dist_to_Vetiver_log	13.21	6.39
Grass_Senescence_Index	8.10	6.21
waterOccurrence	9.62	6.10
TWI_log	0.11	5.41
shannon_diversity	1.81	3.33
saccharumHight_sqrt	5.30	3.09
grazing_sqrt	5.80	1.48
PhragmitesHight_sqrt	7.01	1.43
fire_sqrt	1.73	0.90
extracn_sqrt	0.00	0.00

Distance to *Phragmites* emerged as the most critical variable (Mean Decrease Accuracy = 23.61, Mean Decrease Gini = 11.65), followed closely by elevation (Mean Decrease Accuracy = 20.11, Mean Decrease Gini = 11.08). This ranking emphasizes that both proximity to key vegetation types and specific topographic positioning are fundamental to species occurrence patterns. The dominance of these variables reflects the species' highly specialized microhabitat requirements within the broader grassland ecosystem.

NDVI ranked third in importance (Mean Decrease Accuracy = 14.57, Mean Decrease Gini = 8.74), followed by dist_to_Woodland (Mean Decrease Accuracy = 13.31, Mean Decrease Gini = 8.30) and dist_to_Vetiver (Mean Decrease Accuracy = 13.21, Mean Decrease Gini = 6.39). This combination highlights the species' complex requirements for specific vegetation productivity levels, woodland avoidance, and proximity to diverse tall grass types.

Vetiveria Height showed substantial importance (Mean Decrease Accuracy = 12.31, Mean Decrease Gini = 8.81), reinforcing the critical role of tall grass structure in determining habitat suitability. The relatively high importance of NDMI (Mean Decrease Accuracy = 11.15, Mean Decrease Gini = 9.35) further supports the species' association with specific moisture regimes.

3.3.3.3 *Model performance and validation*

The updated GLM diagnostics for Black-breasted Parrotbill presence data demonstrated excellent model performance with well-behaved residual patterns (Figure 9). The residuals vs. fitted values plot showed appropriate distribution around zero with no systematic bias. The Q-Q plot indicated good adherence to distributional assumptions, while the Scale-Location plot demonstrated stable variance across the prediction range. The residuals vs. leverage plot revealed no highly influential observations, confirming robust parameter estimation.

3.3.3.4 *Spatial distribution patterns and abundance*

The spatial analysis revealed a clustered distribution pattern of the Black-breasted Parrotbill (Figure 10). The species occurs in distinct patches across the Brahmaputra grassland system, with the highest abundances concentrated in specific areas, particularly around the Kaziranga grassland islands, the upper Brahmaputra region in Assam, Manas National Park, and isolated grasslands along the Brahmaputra in Arunachal Pradesh.

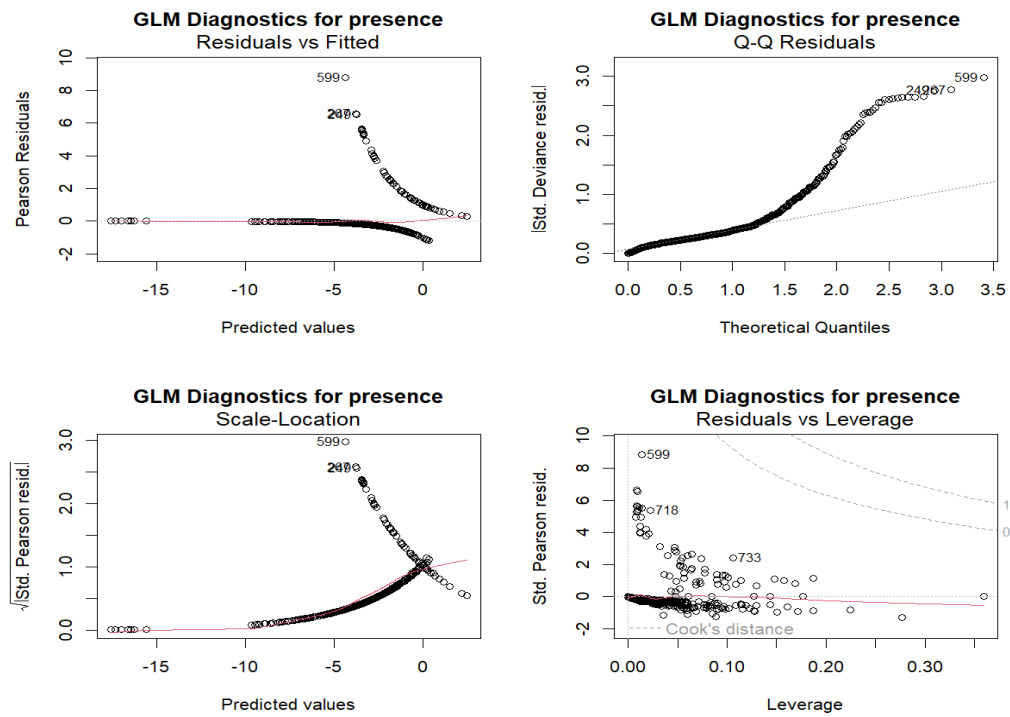


Figure 9 Model Diagnostic Plots for GLM Predicting the Presence Probability of Black-breasted Parrotbill.

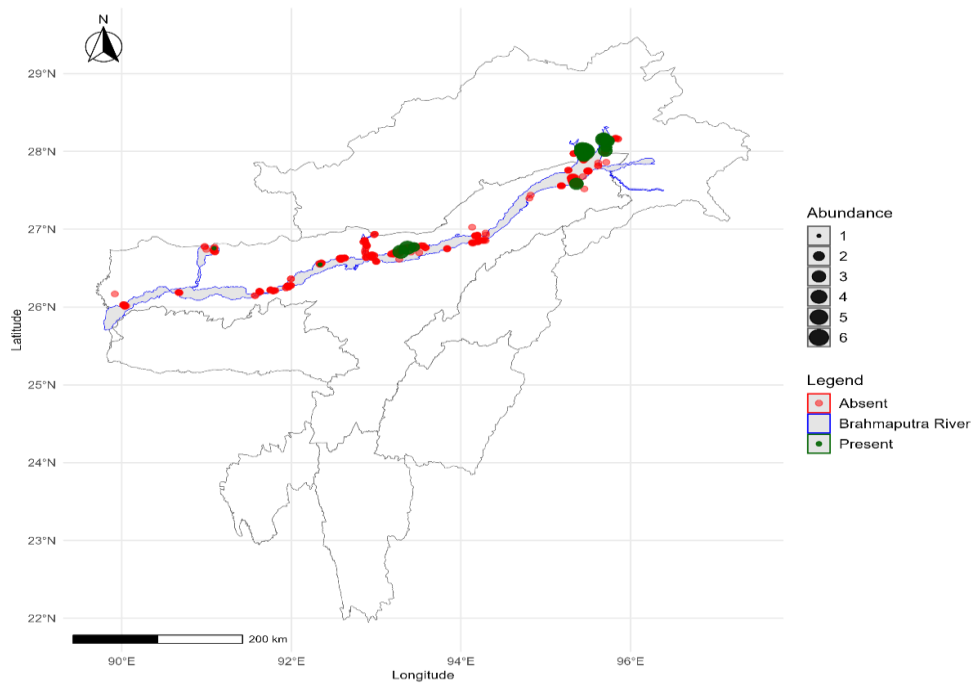


Figure 10 Spatial Distribution of Black-breasted Parrotbill Presence and Sampling Sites Along the study area.

3.3.4 Habitat characteristics and distribution patterns of Marsh Babbler (*Pellorneum palustre*)

3.3.4.1 Generalized Linear Model

The updated GLM analysis revealed highly refined and statistically robust habitat associations for Marsh Babbler presence, demonstrating the species' specialized ecological requirements within the Brahmaputra floodplain ecosystem (Table 7). Among the 18 predictor variables examined, several showed exceptionally strong statistical relationships with species occurrence, providing clear insights into the species' ecological niche.

Table 7 GLM Results for Presence of Marsh Babbler

Predictor	Estimate	Std. Error	z	p-value	
(Intercept)	-41.068	12.502	-3.28	0.001	**
elevation	0.026	0.014	1.81	0.070	.
shannon_diversity	-2.207	1.092	-2.02	0.043	*
NDVI	1.207	5.817	0.21	0.836	
NDMI	-5.202	6.725	-0.77	0.439	
TWI_log	-0.225	0.960	-0.23	0.815	
LST	0.528	0.211	2.50	0.012	*
waterOccurrence	0.135	0.049	2.74	0.006	**
dist_to_WaterBodies_log	0.435	0.319	1.36	0.172	
dist_to_BuiltUp_log	1.707	0.564	3.03	0.002	**
dist_to_Pragmites_log	-2.108	0.532	-3.96	< 0.001	***
dist_to_Woodland_log	-0.119	0.285	-0.42	0.677	
saccharum Height_sqrt	0.228	0.091	2.51	0.012	*
Vetiveria Height_sqrt	0.250	0.121	2.06	0.039	*
Phragmites Height_sqrt	0.503	0.119	4.23	< 0.001	***
grazing_sqrt	-4.597	626.057	-0.01	0.994	
fire_sqrt	-0.921	1.152	-0.80	0.424	
extracn_sqrt	3.376	3,935.252	0.00	0.999	
Grass_Senescence_Index	-1.901	4.673	-0.41	0.684	

Note. * p < .05, ** p < .01, *** p < .001

Phragmites Height emerged as the strongest positive predictor ($\beta = 0.503$, $z = 4.23$, $p < 0.001$), indicating an absolute requirement for tall *Phragmites* reed stands. The companion variable *dist_to_Pragmites* showed the strongest negative association ($\beta = -2.108$, $z = -3.96$, $p < 0.001$), reinforcing the critical importance of immediate proximity to *Phragmites* stands for species occurrence. Additional grass height variables demonstrated significant positive associations: *Vetiveria* Height ($\beta = 0.250$, $z = 2.06$, $p = 0.039$) and *Saccharum* Height ($\beta = 0.228$, $z = 2.51$, $p = 0.012$), indicating the species' preference for diverse tall grass assemblages.

Water occurrence demonstrated a highly significant positive relationship ($\beta = 0.135$, $z = 2.74$, $p = 0.006$), reflecting the species' fundamental association with wetland environments. This finding supports the species' documented preference for marshy ground and proximity to swamps and rivers. LST showed a significant positive association ($\beta = 0.528$, $z = 2.50$, $p = 0.012$), suggesting specific thermal requirements that may relate to optimal wetland conditions.

Distance to built-up areas demonstrated a highly significant positive relationship ($\beta = 1.707$, $z = 3.03$, $p = 0.002$), indicating strong avoidance of human settlements and infrastructure. This finding has critical conservation implications, as it quantifies the species' sensitivity to anthropogenic disturbance and urban encroachment.

Shannon diversity showed a significant negative association ($\beta = -2.207$, $z = -2.02$, $p = 0.043$), suggesting the species prefers relatively homogeneous wetland grassland environments rather than highly heterogeneous landscape mosaics. This preference for landscape uniformity aligns with the species' specialization for specific reed and tall grass habitats.

Elevation showed a marginally significant positive association ($\beta = 0.026$, $z = 1.81$, $p = 0.070$), indicating subtle preferences for specific elevational zones within the floodplain.

3.3.4.2 Variable Importance of Random Forest

The Random Forest analysis provided clarity regarding habitat variable importance, revealing a distinct hierarchy of environmental drivers with *Phragmites*-related variables dominating the importance rankings (Table 8).

Table 8 Random Forest Variable Importance for Presence of Marsh Babbler

Predictor	Mean Decrease Accuracy	Mean Decrease Gini
dist_to_Pragmites_log	22.65	8.70
PhragmitesHeight_sqrt	17.84	7.92
NDVI	14.42	6.65
NDMI	12.91	5.70
Grass_Senescence_Index	9.94	4.38
dist_to_BuiltUp_log	8.57	4.17
LST	10.01	3.97
elevation	11.54	3.88
dist_to_Woodland_log	6.12	3.35
dist_to_WaterBodies_log	5.96	2.80
waterOccurrence	4.92	1.92
TWI_log	2.06	1.76
VetiveriaHeight_sqrt	8.79	1.27
shannon_diversity	3.71	1.26
saccharum Height_sqrt	6.35	0.73
grazing_sqrt	3.86	0.31
fire_sqrt	3.50	0.20
extracn_sqrt	0.00	0.00

Note. Higher values indicate greater importance. Gini importance reflects variable contribution to node purity.

Distance to *Phragmites* emerged as the most critical variable (Mean Decrease Accuracy = 22.65, Mean Decrease Gini = 8.70), followed immediately by Phragmites Height (Mean Decrease Accuracy = 17.84, Mean Decrease Gini = 7.92). This ranking pattern demonstrates the species absolute dependence on *Phragmites* reed stands, both in terms of spatial proximity and structural characteristics. The combined importance of these

variables significantly exceeds other predictors, emphasizing the species' highly specialized niche requirements.

NDVI ranked third in importance (Mean Decrease Accuracy = 14.42, Mean Decrease Gini = 6.65), followed by NDMI (Mean Decrease Accuracy = 12.91, Mean Decrease Gini = 5.70). The prominence of these vegetation indices reflects the species' dependence on productive, well-vegetated wetland grasslands with optimal moisture conditions. Grass_Senescence_Index showed substantial importance (Mean Decrease Accuracy = 9.94, Mean Decrease Gini = 4.38), indicating sensitivity to seasonal vegetation changes and grass phenology.

Elevation demonstrated notable importance (Mean Decrease Accuracy = 11.54, Mean Decrease Gini = 3.88), supporting the GLM findings of subtle topographic preferences. LST (Mean Decrease Accuracy = 10.01, Mean Decrease Gini = 3.97) and dist_to_BuiltUp (Mean Decrease Accuracy = 8.57, Mean Decrease Gini = 4.17) further emphasize the species' requirements for specific thermal conditions and anthropogenic avoidance.

3.3.4.3 Model Performance and Validation

The GLM diagnostics for Marsh Babbler presence data demonstrated robust model performance with appropriate residual patterns (Figure 11). The residuals vs. fitted values plot showed good distribution around zero with minimal systematic bias. The Q-Q plot indicated reasonable adherence to distributional assumptions, while the Scale-Location plot demonstrated stable variance across the prediction range. The residuals vs. leverage plot revealed no highly influential observations, confirming reliable parameter estimation.

3.3.4.4 Spatial Distribution Patterns and Ecological Relationships

The distribution of the Marsh Babbler is comparatively limited when compared to the other study species (Figure 12). It is primarily confined to reed patches in the upper Brahmaputra region of Arunachal Pradesh. A more prominent distribution is observed in and around Dibru-Saikhowa National Park, with a few isolated occurrences recorded in other regions as well.

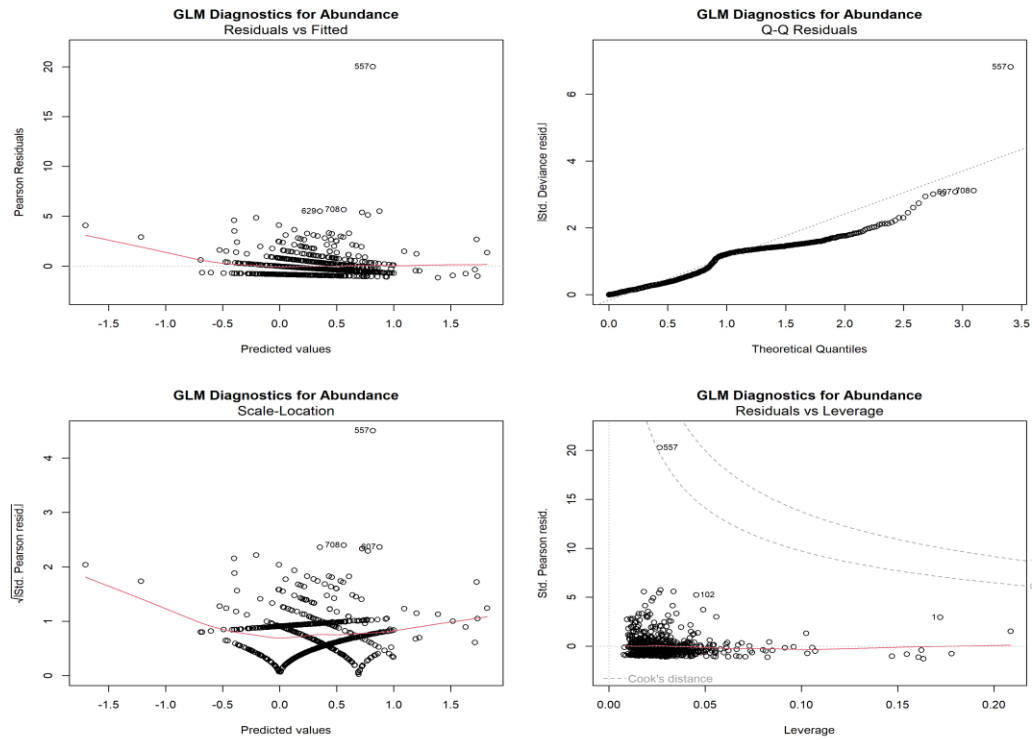


Figure 11 Model Diagnostic Plots for GLM Predicting the Presence Probability of Marsh Babbler.

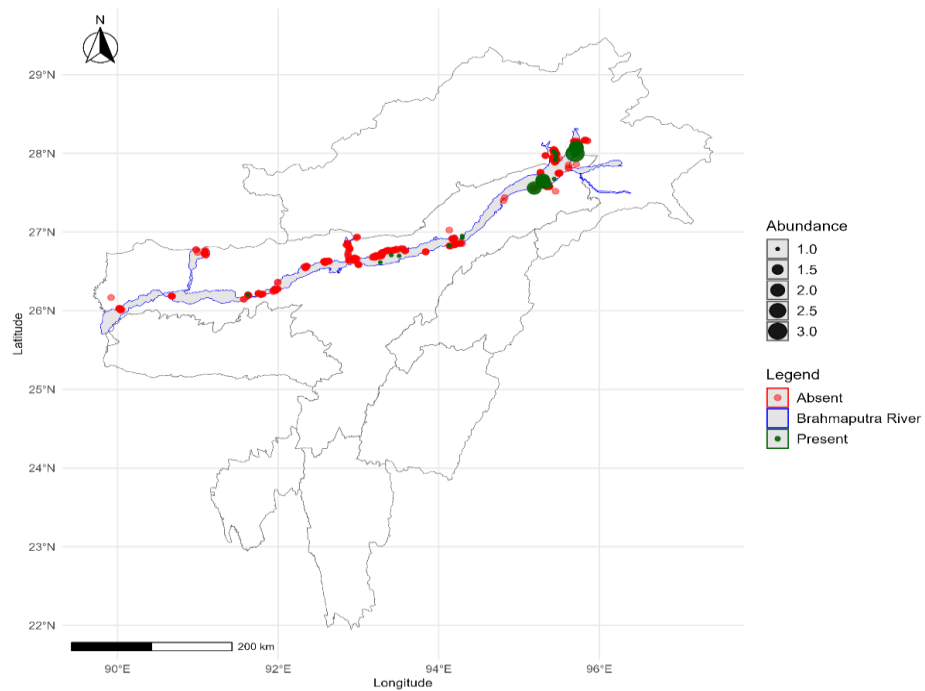


Figure 12 Spatial Distribution of Marsh Babbler Presence and Sampling Sites Along the study area.

3.4 Discussion

The comprehensive assessment of habitat characteristics for Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*) reveals distinct yet overlapping ecological requirements that underscore the complexity of grassland bird conservation in the Brahmaputra floodplains.

3.4.1 Species-specific habitat requirements and ecological specialization

3.4.1.1 Jerdon's Babbler

The findings demonstrate that Jerdon's Babbler exhibits the highest degree of habitat specialization among the three study species, with an overwhelming dependence on *Saccharum* grasslands. The exceptionally strong association between Jerdon's Babbler presence and *Saccharum* height ($\beta = 0.314$, $z = 9.64$, $p < 0.001$) and the concurrent negative relationship with distance to *Saccharum* patches ($\beta = -0.389$, $z = -4.73$, $p < 0.001$) confirms this species' absolute requirement for proximity to tall *Saccharum* stands. This specialization aligns with previous documentation of the species' preference for dense, contiguous grasslands (Akash et al., 2018; Dehar et al., 2024) and supports the assertion that Jerdon's Babbler represents a flagship species for *Saccharum*-dominated grassland conservation in the region.

3.4.1.2 Black-breasted Parrotbill

Black-breasted Parrotbill exhibits a distinct habitat profile characterized by strong associations with *Phragmites* reed beds combined with active avoidance of wooded areas. The species' absolute requirement for proximity to *Phragmites* stands ($\beta = -0.455$, $z = -5.06$, $p < 0.001$) aligns with previous field observations that documented the species' restriction to reed-dominated grasslands (Allen, 2002).

The species' restriction to "nal" grasslands comprised of *Phragmites karka* and *Arundo donax* has been previously documented, with local communities extensively harvesting these grasses, highlighting the need for sustainable management practices that ensure sufficient regeneration.

3.4.1.3 Marsh Babbler

Marsh Babbler emerges as the most wetland-dependent of the three species, with *Phragmites* height representing the strongest positive predictor ($\beta = 0.503$, $z = 4.23$, $p < 0.001$) and distance to *Phragmites* showing the strongest negative association ($\beta = -2.108$, $z = -3.96$, $p < 0.001$). Endemic to the Brahmaputra floodplain and its associated tributaries.

3.4.2 Spatial distribution patterns and conservation priorities

The clustered distribution patterns observed for all three species, with concentrations in the Kaziranga region, upper Brahmaputra areas of Assam, and isolated grasslands in Arunachal Pradesh, reflect the fragmented nature of suitable habitat across the landscape. The Brahmaputra floodplains support many threatened grassland-dependent species like Bengal Florican, Manipur Bush Quail, Swamp Grass-babbler, Eastern Grass Owl (Allen, 2002; Skowno & Bond, 2003) emphasizing the global conservation significance of this ecosystem. The spatial aggregation of suitable habitat patches highlights the importance of maintaining connectivity between remnant grassland areas and protecting core habitat areas from further degradation.

3.4.3 Conclusion

This comprehensive habitat assessment reveals that Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler exhibit distinct yet overlapping habitat requirements that reflect their evolutionary adaptations to the dynamic Brahmaputra floodplain ecosystem. The strong associations with specific vegetation types (*Saccharum* for Jerdon's Babbler, *Phragmites* for the other two species), elevation preferences, and sensitivity to anthropogenic disturbance provide clear guidance for evidence-based conservation planning.

The consistent negative impacts of grazing and fire across all species, combined with their requirements for tall, dense grassland vegetation, underscore the urgent need for protected area designation and management protocols that prioritize habitat quality over short-term economic gains. The methodological insights gained from comparative GLM

and Random Forest analyses demonstrate the value of multi-algorithm approaches for understanding complex species-habitat relationships in threatened grassland ecosystems.

The spatial clustering of suitable habitat and the specialized requirements of each species support a landscape-scale conservation approach that maintains habitat heterogeneity while ensuring sufficient areas of high-quality, species-specific habitat. As the Brahmaputra floodplains face increasing pressures from development, climate change, and agricultural expansion, the habitat requirements documented in this study provide essential baseline data for guiding conservation investments and policy decisions that will determine the long-term survival of these globally threatened grassland specialists.

Chapter 4

CHAPTER 4

THREATS TO THE SPECIES AND ITS HABITATS

This chapter addresses the second objective of the thesis, which is “*To evaluate the threats to these select three species of birds and their habitats*”.

4.1 Introduction

The accelerating decline of global biodiversity has positioned threat assessment as a cornerstone of modern conservation planning and management. Identifying and quantifying threats to species and ecosystems represents a critical first step in prioritizing conservation actions, allocating limited resources effectively, and developing targeted management strategies (Salafsky et al., 2019). As conservation practitioners and scientists increasingly recognize, a comprehensive understanding of threatening processes is essential for developing evidence based conservation interventions that can meaningfully address the immediate causes of biodiversity loss (Game et al., 2013; Sarkar et al., 2006). In the context of avian conservation, threat assessment has become particularly urgent given the alarming evidence of widespread population declines among bird species globally, with grassland dependent species experiencing some of the steepest declines across all habitat types (Rosenberg et al., 2019).

Grassland ecosystems rank among the most threatened and least protected biomes worldwide, with grassland-dependent bird species experiencing population declines that exceed those of forest and wetland specialists (Henwood, 2010; Sauer, Pardieck, et al., 2017). The grassland specialists in India have declined by more than 50 percent, (Bharadwaj et al., 2024). These declines reflect the cumulative impacts of multiple stressors, including habitat conversion, agricultural intensification, fire, altered disturbance regimes, climate change, and invasive species (Brennan & Kuvlesky, 2005).

Fire represents one of the most significant anthropogenic and natural threats to grassland ecosystems worldwide, with profound implications for biodiversity conservation and habitat integrity (Yan & Liu, 2021). In the context of threatened grassland birds, fire disturbance can have both beneficial and negative effects, depending on intensity, frequency, and timing relative to critical life history stages (Beal-Neves et al., 2020).

Understanding fire patterns and their impact on endangered species habitat is crucial for developing effective conservation strategies (Doherty et al., 2024).

The Brahmaputra floodplains of Northeast India support one of the world's most significant grassland bird communities, hosting 220 bird species, several of which are grassland-dependent, including 20 globally threatened species (Narasimmarajan et al., 2013). This unique ecosystem, characterized by its dynamic river channel system and annually flooded grasslands, provides critical habitat for several endemic and threatened species that have evolved specialized adaptations to this fluctuating environment. However, these same characteristics that make the Brahmaputra grasslands globally significant for avian diversity also render them particularly vulnerable to anthropogenic threats and environmental changes.

The Brahmaputra grassland ecosystem faces an unprecedented array of anthropogenic threats that operate across multiple spatial and temporal scales the trend is similar like many global scenario (Douglas et al., 2023). These direct threats are compounded by landscape-level changes including, land use changes, and mining operations that destabilize riverine habitats, upstream dam construction that alters natural flooding regimes (Pradhan et al., 2021c), and climate change impacts that affect precipitation patterns and temperature regimes.

Agricultural expansion represents one of the most pervasive threats to grassland birds in the Brahmaputra basin, with continuing rapid conversion of natural grasslands to cropland observed throughout the region. This transformation not only results in direct habitat loss but also creates landscape fragmentation that reduces habitat connectivity. The intensification of agricultural practices, including increased pesticide use, further threatens grassland bird populations through direct toxicity effects and reductions in arthropod prey availability (Mineau & Whiteside, 2013).

The potential construction of dams and water control structures represents another critical threat category affecting the Brahmaputra grassland ecosystem. Upstream dam construction alters natural flood pulses that are essential for maintaining the dynamic grassland habitats upon which target species depend (van Oorschot et al., 2018). These hydrological modifications affect sediment transport, nutrient cycling, and the formation

of new grassland areas on river islands and floodplains. Climate change compounds these impacts by altering precipitation patterns and increasing the frequency and intensity of extreme weather events, with projections indicating that 66-73% of bird species in India will experience northward or elevational range shifts by 2070 (Kumar et al., 2023).

Climate change represents an overarching threat that interacts synergistically with other stressors to increase the vulnerability of grassland bird populations. Warming temperatures and altered precipitation patterns affect multiple aspects of avian ecology, including breeding, phenology, food availability, habitat suitability, and the geographic distribution of suitable climate space (Both et al., 2006; Jiguet et al., 2007). For species with specialized habitat requirements like the three focal species in this study, climate change may result in mismatches between optimal climatic conditions and suitable habitat, potentially leading to local extinctions or range contractions.

Invasive species represent another emerging threat category that may increase in importance under changing environmental conditions. The spread of invasive plant species can alter grassland structure and composition, potentially reducing habitat suitability for specialist species while favouring more generalist taxa (DiTomaso, 2000). Climate change may facilitate the establishment and spread of invasive species by creating novel environmental conditions that favour non-native taxa over indigenous grassland communities.

4.2 Methods

4.2.1 Anthropogenic pressure

The methodology for investigating anthropogenic pressure on the study species is consistent with that described in Sections 3.2.6 (Generalized Linear Models) and 3.2.7 (Random Forest Analysis) of the previous chapter. The analysis primarily focused on ground-reported fire incidents, grass extraction, mining activity, and proximity to urban areas.

4.2.2 Fire data collection and processing

Fire analysis utilized the Delta Normalized Burn Ratio (dNBR) methodology (Miller & Thode, 2007). The dNBR combines Near-Infrared (NIR) and Short-Wave

Infrared (SWIR) wavelengths to detect burned areas and quantify fire severity. The technique exploits the spectral contrast between healthy vegetation (high NIR, low SWIR reflectance) and burned areas (low NIR, high SWIR reflectance).

Fire severity was classified into discrete categories following established protocols: moderate-low severity (Class 3) and moderate-high severity (Class 4), representing threshold values that effectively discriminate fire impact levels in grassland ecosystems (Escuin et al., 2008). This classification system has been validated across multiple ecosystems and provides consistent results.

Fire datasets generated from sentinel 2 spanning 2018-2023 were compiled from monthly dNBR images, providing comprehensive temporal coverage of fire patterns. The temporal resolution enables analysis of seasonal fire patterns, inter-annual variability, and long-term trends critical for understanding fire regime characteristics (Villar-Hernández et al., 2024).

4.2.2.1 Remote Sensing and Spatial Analysis

Google Earth Engine served as the primary platform for fire analysis, providing cloud-based processing capabilities essential for handling large-scale geospatial datasets (Arsirii et al., 2022). Image collections were systematically processed using cloud masking algorithms to ensure data quality and minimize atmospheric interference.

4.2.2.2 Fire Frequency and Hotspot Detection Analysis

Fire frequency mapping constituted a core component of the threat assessment, implemented through pixel-wise summation of binary fire masks across the study period. Fire hotspot analysis utilized spatial statistical methods to identify areas with significantly higher fire occurrence than expected by chance (Getis & Ord, 1992). The methodology incorporated percentile-based thresholds to classify fire intensity levels:

1. **Low Fire Areas:** Below 75th percentile
2. **Moderate Fire Areas:** 75th-90th percentile
3. **High Fire Areas:** 90th-95th percentile
4. **Extreme Fire Areas:** Above 95th percentile

Monthly fire patterns were analysed to identify seasonal trends and peak fire activity periods. Comparative analysis of fire patterns between protected and unprotected areas has performed to provides insights into conservation effectiveness and management priorities. Fire impact assessment was conducted for each land cover class to understand habitat-specific fire vulnerability and inform species-specific conservation strategies. The analysis focused particularly on grassland classes most relevant to target species

4.2.3 Climatic threats

Habitat shifts and potential changes were evaluated using ensemble Niche modelling for each study species. Future projections were also made under different Shared Socioeconomic Pathways (SSPs). A detailed analysis and interpretation of these results are presented separately in the following chapter.

4.2.4 Documentation of other threats during field survey

During the field visit, potential threats to the study area were systematically recorded using direct observation, structured checklists, and GPS-enabled photographic documentation. Key biotic and abiotic stressors such as habitat degradation, pollution, invasive species, anthropogenic disturbances, and natural hazards were identified and geotagged. Interviews with local stakeholders supplemented observational data to capture socio-environmental pressures.

4.3 Results

4.3.1 Anthropogenic threats

4.3.1.1 Grazing pressure

Livestock grazing emerged as one of the most severe threats across all three species, consistently showing highly significant negative associations with species presence. Jerdon's Babbler exhibited the strongest negative response to grazing pressure ($\beta = -0.369$, $z = -5.13$, $p < 0.001$), indicating severe impacts on species occurrence. Black-breasted Parrotbill showed a moderate negative association with grazing ($\beta = -0.078$, $z = -1.14$, $p = 0.254$), while the impact on Marsh Babbler could not be reliably estimated due to data limitations ($\beta = -4.597$, $z = -0.01$, $p = 0.994$). Random Forest variable importance rankings

confirmed grazing as a critical threat factor for Jerdon's Babbler (Mean Decrease Accuracy = 15.01), demonstrating substantial impact on habitat suitability.

4.3.1.2 *Fire regimes*

Fire frequency and intensity represented another major anthropogenic threat affecting all target species (Figure 13). Jerdon's Babbler demonstrated highly significant negative associations with fire occurrence ($\beta = -0.312$, $z = -3.91$, $p < 0.001$), while Black-breasted Parrotbill showed marginally significant negative effects ($\beta = -0.190$, $z = -1.94$, $p = 0.052$). Marsh Babbler exhibited negative associations with fire impacts ($\beta = -0.921$, $z = -0.80$, $p = 0.424$), though the relationship was not statistically significant. The Random Forest analysis indicated fire as a moderate threat factor across species, with variable importance values ranging from 1.73 to 8.60 for Mean Decrease Accuracy.

The Spatial fire analysis revealed significant temporal and spatial patterns in fire occurrence across the Brahmaputra floodplains (Figure 14), with profound implications for the three target species. Fire incidents demonstrated a seasonal pattern (Figure 14), with the pre-monsoon period (March-May) experiencing the highest fire activity, accounting for 198,000 hectares of burned area, representing approximately 58% of the total annual fire impact. April emerged as the peak fire month, with 67,500 hectares affected, coinciding with the potential breeding season for Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler.

The fire data analysis revealed differential impacts across vegetation types (Figure 17), with *Saccharum* grasslands, one of the preferred habitat of all three target species experiencing substantial fire pressure during the pre-monsoon period (Figure 16). The protected areas demonstrated marginally lower fire frequencies compared to unprotected grasslands (Figure 15), with protected areas experiencing 25,000 hectares of burned area during the pre-monsoon season compared to 43,000 hectares in unprotected areas.

Particularly concerning is the impact on *Phragmites* vegetation, which experienced peak fire activity of 17,000 hectares in April. This vegetation type serves as critical habitat for Black-breasted Parrotbill, and Marsh Babbler, which depends on tall reed beds for nesting and foraging.



Figure 13 Fire Hotspot Zones Based on Frequency Analysis in the Study Area

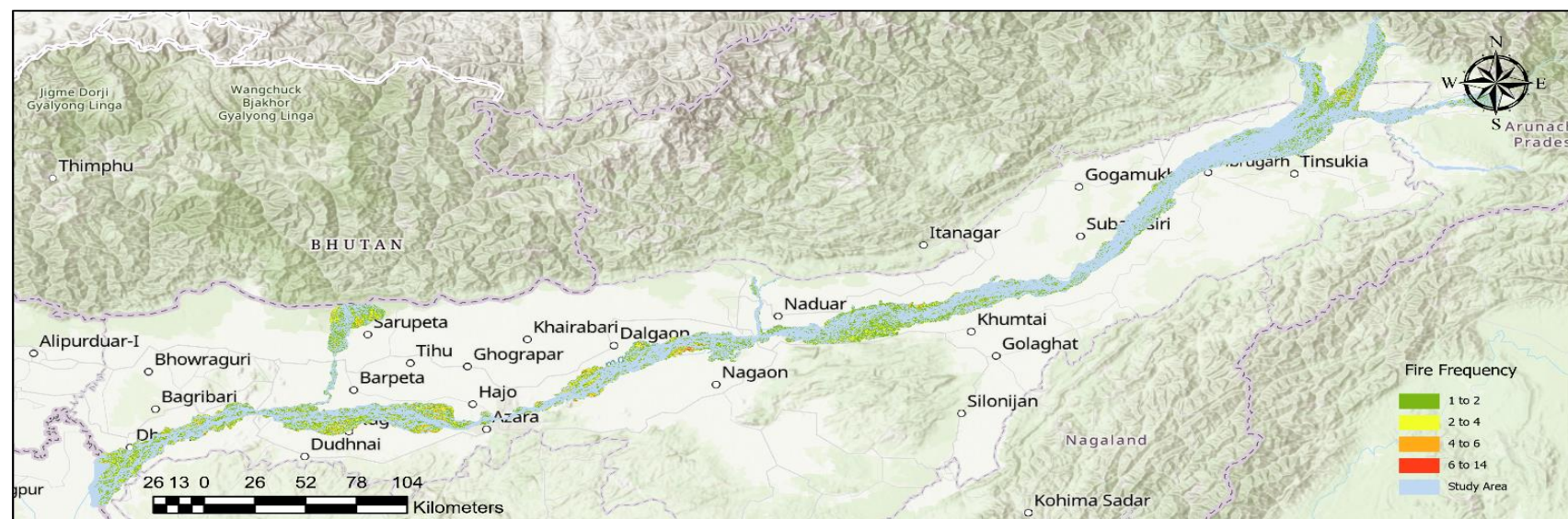


Figure 14 Frequency of fire events across the landscape (2018–2023).

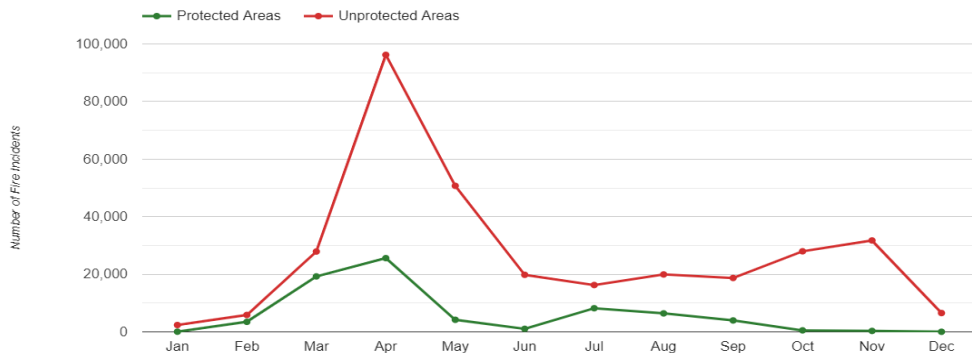


Figure 15 Monthly trends in fire incidence across protected and non-protected landscapes

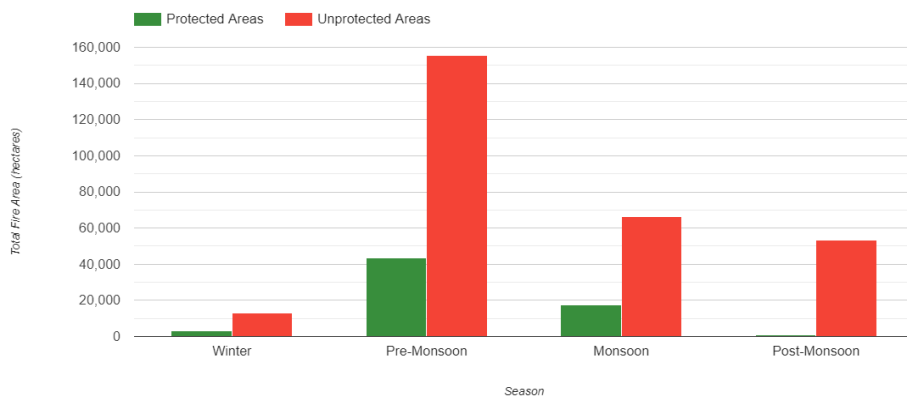


Figure 16 Seasonal variation in fire-affected area across protected and unprotected regions

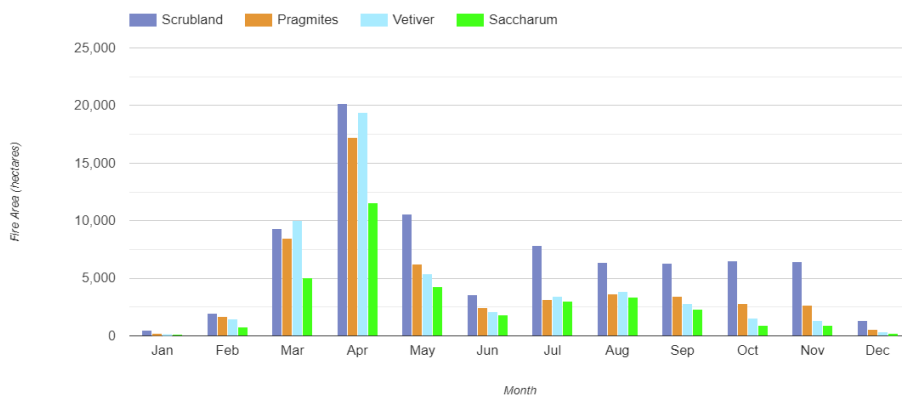


Figure 17 Spatial distribution of fire-affected areas in grassland classes

4.3.1.3 Agricultural Expansion and Habitat Conversion

Agricultural encroachment emerged as the most pervasive threat to grassland bird habitats in the Brahmaputra floodplains (Parengal, et al., 2025). Field observations documented extensive conversion of native grasslands to rice cultivation, particularly on the char and chapori (riverine islands) that serve as crucial refugia for threatened species.

The impact on Black-breasted Parrotbill populations has been particularly severe, with the species now largely confined to protected areas where tall elephant grass habitat remains intact. Marsh Babbler populations have shown similar declines in areas where agricultural intensification has occurred. The species' preference for dense wetland edges and tall grass communities makes it particularly vulnerable to habitat fragmentation caused by agricultural expansion.

4.3.2 Indirect threats and cumulative impacts

4.3.2.1 Climate Change Effects on Habitat Suitability

Climate change projections for Northeast India suggest significant implications for the distribution and habitat availability of grassland bird species, particularly under higher-emission SSP scenarios. Detailed results are presented in the results section of Chapter 5.

4.3.2.2 Anthropogenic Disturbance and Human Population Pressure

The GLM analyses revealed significant species-specific responses to anthropogenic disturbance, particularly in relation to proximity to built-up areas (

Table 3, Table 5, and Table 7). Among the three target species, Jerdon's Babbler demonstrated a weaker but positive response to distance from built-up areas (coefficient = 0.179 ± 0.151 , $z = 1.18$, $p = 0.237$), though this relationship was not statistically significant. Black-breasted Parrotbill showed a non-significant negative association with log-transformed distance to built-up areas (coefficient = -0.075 ± 0.155 , $z = -0.49$, $p = 0.626$), suggesting this species may be more tolerant of human proximity or potentially benefits from edge effects created by anthropogenic landscapes. Marsh Babbler showed the strongest positive association with distance from built-up areas, with a significant coefficient estimate of 1.707 ± 0.564 ($z = 3.03$, $p = 0.002$). This finding suggests that Marsh Babbler populations are significantly higher in areas farther from human settlements, indicating a strong negative response to urbanization pressure.

4.4 Discussion

The comprehensive threat assessment reveals a complex web of interconnected pressures affecting the three target grassland bird species in the Brahmaputra floodplains. The findings demonstrate that fire regimes, while historically natural components of grassland ecosystems, have become increasingly problematic due to anthropogenic alterations in timing, frequency, and intensity. The peak fire activity during April, coinciding with the breeding season, represents a critical conservation challenge that requires immediate attention.

The dominance of agricultural expansion as a threat aligns with global patterns affecting grassland birds. Agriculture represents the primary threat to grassland birds worldwide, with approximately 75% of studies identifying agricultural impacts as the leading cause of population declines (Douglas et al., 2023). The Brahmaputra floodplains exemplify this global pattern, with the conversion of native grasslands to rice cultivation eliminating habitat while simultaneously increasing edge effects and fragmentation.

The climate change projections for Northeast India present particularly concerning implications for grassland bird conservation. The predicted northward and upward shifts in species distributions pose significant challenges for conservation planning, as suitable habitat at higher elevations or northern latitudes may not be available. The comprehensive

climate change assessment indicates that grassland species face particular vulnerability due to their limited dispersal capacity and specific habitat requirements (Deomurari et al., 2023).

The interaction between climate change and other threats creates compound impacts that threaten species persistence. Rising temperatures may increase fire frequency and intensity, while altered precipitation patterns could affect the invertebrate prey communities upon which the target species depend

Prabhakaran et al. (2024) found that in community reserves, vegetation diversity is strongly shaped by landscape structure and human interventions, with complex patch shapes supporting higher species richness, while greater disturbance reduces diversity. These findings underscore how habitat fragmentation, patch simplification, and local human pressures can alter ecosystem integrity. In the context of the three threatened grassland birds along the Brahmaputra, similar processes such as land-use change, fire, grazing, and human encroachment pose critical threats by reducing habitat quality and availability, thereby constraining species persistence and recovery.

The intensity of human pressure on Brahmaputra floodplain grasslands reflects broader patterns of development pressure across South Asia. The anthropogenic disturbance assessment confirms that human activities consistently reduce functional diversity in bird communities, with grassland species showing particular sensitivity to disturbance (Matuoka et al., 2020).

The fragmentation of grassland habitats through linear infrastructure development represents an emerging threat that requires proactive management. Research on infrastructure impacts demonstrates that even low-density infrastructure can significantly affect grassland bird populations through barrier effects and increased predation risk (Marques et al., 2020).

The threat assessment findings have direct implications for grassland bird conservation strategies in the Brahmaputra floodplains. The identification of fire timing as a critical factor suggests that prescribed burning programs could be implemented to reduce wildfire risk while maintaining grassland ecosystem integrity. Fire management research indicates that controlled burning at appropriate intervals can maintain habitat heterogeneity while reducing the risk of catastrophic wildfires (Beal-Neves et al., 2020).

The cumulative impact assessment demonstrates that effective conservation requires addressing multiple threats simultaneously through integrated management approaches. The dynamic nature of threats in the Brahmaputra floodplains demands adaptive management strategies that can respond to changing conditions while maintaining long-term conservation objectives. The success of conservation efforts will ultimately depend on the ability to balance human needs with the protection of critical grassland habitats and the unique bird communities they support.

Chapter 5

CHAPTER 5

CURRENT AND FUTURE POTENTIAL HABITATS AND POPULATION RECOVERY SITES

This chapter addresses the third objective of the thesis, which is “*To predict the current and future potential habitats of these birds and find potential population recovery sites*”.

5.1 Introduction

Understanding the spatial and temporal patterns of species distribution is fundamental to effective conservation planning, particularly for threatened species facing the dual pressures of habitat loss and climate change (Guisan et al., 2013). Species distribution models (SDMs) have emerged as critical tools for conservation decision-making, providing accurate predictions of species occurrence across space and time that are essential for effective conservation planning (Crispim et al., 2024). For grassland bird species, which are experiencing some of the most declines globally, predictive habitat modelling has become increasingly vital for identifying priority areas for conservation action and developing targeted recovery strategies (Hao et al., 2019; Monroe et al., 2021).

More than half of bird species that depend on grasslands for breeding habitat are in steep decline, more than any other terrestrial biome (“Grassland Birds,” 2025). The three focal species of this study: Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*), exemplify this crisis. Jerdon's Babbler, listed as Vulnerable on the IUCN Red List since 1994, occurs in three disjunct populations along the river Indus and its tributaries in Pakistan, in the terai of Nepal, and the Ganga-Brahmaputra floodplain in North-east India, with large tracts of natural swamps and wet grassland having been destroyed or degraded throughout its range (BirdLife International, 2025). The species was notably rediscovered in Myanmar in 2014 after being presumed extinct since 1941, highlighting both the cryptic nature of these grassland specialists and their precarious conservation status (Rheindt et al., 2014b).

Similarly, the Black-breasted Parrotbill is thought to be in rapid decline as a result of extensive loss and degradation of its tall grassland habitat, classified as Vulnerable

(BirdLife International, 2024). This species inhabits inland wetlands and grasslands of the Brahmaputra valley foothills (up to 150m ASL) in Assam and Arunachal Pradesh, India, and has possibly undergone extirpation from Bangladesh and Nepal. The Marsh Babbler, endemic to the Brahmaputra floodplain, its associated tributaries and adjacent hill ranges, is suspected to be in rapid decline due to widespread loss of its tall grassland habitat, with rapid and extensive loss and modification of tall grasslands and reed swamp throughout its limited range as the main threat (BirdLife International, 2021).

The urgency of developing robust predictive models for these species is underscored by the accelerating pace of environmental change in the Brahmaputra basin. The Brahmaputra basin is characterized by high seasonal variability in flow, sediment transport and channel configuration, with climate change projected to affect freshwater availability through changes in temperature, precipitation, and CO₂ concentration, and climate change will have marked effects on meltwater in the Indus Basin and may result in increased flood risk in the Brahmaputra Basin. These hydrological changes directly impact the wetland and grassland habitats upon which the focal species depend.

5.1.1 Advances in species distribution modelling

Contemporary approaches to species distribution modelling have evolved considerably from single-algorithm implementations to sophisticated ensemble methods that account for model uncertainty and improve predictive performance. The idea of combining predictions from different models into an ensemble has gained considerable popularity in species distribution modelling (Araújo & New, 2007; Hao et al., 2019). Recent benchmark studies with reproducible code have demonstrated that the top performing method was an ensemble of tuned individual models, while ensembles built using the BIOMOD framework with default parameters performed no better than single moderate performing models (Valavi et al., 2022).

For species with limited occurrence data, such as our focal grassland birds, ensemble modelling approaches offer particular advantages. In regions of high conservation need but limited data, species distribution models using habitat suitability approaches have proven effective, with extensive literature reviews used to determine model parameters for habitat modelling, and habitat relationships implemented in GIS

using land cover covariates (Prosser et al., 2018). Recent studies comparing Biomod2 with other approaches like Maxent and GARP have shown that Biomod2 obtained the best AUC, KAPPA and TSS values of larger than 0.926, making it the preferred choice for constructing ensemble models (Huang et al., 2023). On average, six individual models are used in ensembles (median = 6 and mean = 6.2), with GLMs most frequently used, followed closely by BRTs, RFs and GAMs (Hao et al., 2019).

5.1.2 Climate change scenarios and future projections

The development of robust future habitat predictions requires careful consideration of climate change scenarios and their associated uncertainties. The international climate research community has developed Shared Socioeconomic Pathways (SSPs) that examine how global society, demographics and economics might change over the next century, which are designed to be complementary to Representative Concentration Pathways (RCPs) that set pathways for greenhouse gas concentrations and the amount of warming that could occur by the end of the century (Riahi et al., 2017; Van Vuuren et al., 2011).

Climate change studies on bird species have shown that high temperature and low rainfall in future climatic scenarios are expected to decrease taxonomic, phylogenetic, and functional diversity of bird species, leading to a restructuring of species assemblages around the world (Dantas-Queiroz et al., 2021; Mota et al., 2022). Recent assessments of North American birds under global warming scenarios (1.5°C optimistic mitigation scenario versus 3.0°C unmitigated scenario) demonstrate that effective conservation requires both adaptation and mitigation to improve species resilience, with vulnerability assessed through modeled range loss and gain based on species-specific dispersal abilities (Bateman et al., 2020).

5.1.3 Population recovery site identification

Beyond predicting current and future habitat suitability, a crucial component of conservation planning involves identifying optimal sites for population recovery and restoration efforts. Despite committed action by many in past decades, recent reviews show little progress in slowing species declines, and substantial increases in ambition and the application of tools across all elements of the species conservation cycle, Assess, Plan, and Act, are urgently needed to create swift and lasting positive change for species

(Byers et al., 2022). Recovery plans set out the research and management actions necessary to stop the decline of, and support the recovery of, listed threatened species or threatened ecosystems, with the aim to maximize long-term survival in the wild.

The integration of species distribution modelling with systematic conservation planning has enabled more strategic approaches to recovery site identification. High-resolution species distribution modelling can reveal spatio-temporal variability of habitat suitability across phenological phases and over multiple years, providing critical information for conservation planning (Kumar et al., 2021). Studies of grassland bird conservation have demonstrated the importance of habitat availability, grazing management, and linear infrastructure impacts in explaining spatial and temporal variation in population density, with management effects varying across landscapes (Marques et al., 2020).

5.2 Methods

5.2.1 Study area

For niche modelling to forecast potential habitat distribution, the study area encompasses the entire Northeastern region of India and extends into key contiguous ecoregions, including adjoining parts of Myanmar and the Eastern Gangetic Plains. This region includes lowland floodplains, swamp forests, moist and dry deciduous forests, subtropical and montane forests, as well as savanna and grassland ecosystems. Key ecoregions are the Irrawaddy freshwater swamp forests, Upper and Lower Gangetic Plains moist deciduous forests, Brahmaputra Valley semi-evergreen forests, Terai-Duar savanna and grasslands, and Himalayan subtropical broadleaf forests. Also included are the Arunachal Pradesh-Manipur-Kachin rain forests, Nagaland subtropical forests, Sundarbans freshwater swamp forests, and Myanmar's moist and dry deciduous forests, pine forests, and coastal rain forests. These varied ecosystems support high levels of endemism and biodiversity, forming critical corridors for species movement, ecological connectivity, and regional conservation efforts.

5.2.2 Data acquisition

The occurrence data from field surveys, described in detail in the preceding chapters, were used to assess habitat characteristics and species presence. These surveys included Fixed-Radius Point Count methods, Call Playback techniques, and opportunistic

observations. All records were integrated to obtain the maximum possible number of occurrence points for developing the niche models.

To ensure comprehensive coverage and robust dataset development, extensive secondary data collection was undertaken to supplement primary field observations and provide broader temporal and spatial context for species distribution patterns. This approach involved systematic literature reviews and database searches to gather historical distribution records for all three target species (Narwade et al., 2011).

The integration of citizen science data proved invaluable for expanding the geographic scope of the analysis, occurrence records sourced from the Global Biodiversity Information Facility (GBIF) database (<http://www.gbif.org>), significantly enhancing data comprehensiveness and providing insights into species distribution patterns beyond the immediate study area. Additional occurrence data were systematically collected from eBird (<https://ebird.org>) and other online biodiversity databases to ensure maximum spatial coverage and temporal depth. All secondary data sources were subjected to rigorous quality control procedures, including verification of taxonomic identity, geographic accuracy, and temporal reliability to maintain dataset integrity and prevent the inclusion of misidentified or geographically inaccurate records.

5.2.3 Remote sensing and geographic information system analysis

Comprehensive spatial analysis was conducted using multi-temporal satellite imagery and advanced Geographic Information System (GIS) techniques to characterize habitat conditions and landscape features across the study area. Multi-temporal Sentinel-2 Surface Reflectance data were systematically processed within ArcGIS Pro to compute the Normalized Difference Vegetation Index (NDVI), serving as a key indicator of vegetation health and grassland productivity across the Brahmaputra floodplains. The NDVI was calculated using the standard formula:

$$NDVI = \frac{B8 - B4}{B8 + B4}$$

where B8 represents the near-infrared band and B4 corresponds to the red band, providing quantitative measures of vegetation vigor that could be correlated with habitat suitability for each target species.

Land cover classifications were derived from multiple authoritative sources to ensure comprehensive coverage and accuracy. Built-up areas and urban development patterns were extracted from the World Settlement Footprint (WSF2015) dataset (Cohen et al., 2020), while detailed vegetation and land cover classifications, including grasslands, wetlands, and sandy riverine areas, were obtained from the Copernicus Global Land Cover dataset (2019) (Buchhorn et al., 2020). To improve spatial accuracy and capture local habitat heterogeneity that might be missed by global datasets, additional manual digitization was performed for key habitat types, particularly focusing on the identification of specific grassland types known to be preferred by each target species.

Water body delineation was accomplished using the Global Surface Water Dataset, with analysis restricted to water features exhibiting at least six months of annual water presence to ensure relevance to the ecology of the target species (Pekel et al., 2016). Euclidean distance analysis was systematically performed in ArcGIS to quantify spatial relationships between survey locations and various landscape features including urban areas, water bodies, and different habitat types. Square-root transformation was applied to all distance rasters to standardize data distributions for subsequent habitat modelling applications. All spatial layers and climate-related raster data were carefully clipped to the geographical extent of the Indo-Malayan biogeographic realm to ensure regional relevance and computational efficiency.

5.2.4 Species distribution modelling framework

Species distribution modelling was conducted using the BIOMOD2 platform in R, which provides a comprehensive ensemble modelling framework that addresses methodological uncertainties inherent in single-algorithm approaches (Khan & Verma, 2022; Thuiller et al., 2014). The ensemble approach was particularly appropriate for this study given the cryptic nature of the target species and the potential for varying model performance across different algorithms and habitat types. Pseudo-absence points were systematically generated using a 10:1 ratio relative to presence points, employing the Surface Range Envelope (SRE) strategy to ensure representative sampling of the environmental space while avoiding spatial clustering that could bias model performance (Saranya et al., 2021).

Model validation employed a robust 5-fold cross-validation approach combined with geographically stratified sampling to account for potential spatial autocorrelation in the dataset and ensure model transferability across different regions within the study area. Two complementary machine learning algorithms, SRE and XGBoost, were systematically employed with optimization strategies including both the BigBoss strategy (utilizing generalized parameters) and the Tuned strategy (implementing dataset-specific optimization) to enhance predictive accuracy and model robustness. The ensemble modelling framework incorporated multiple algorithms including EMmean, EMcv, EMci, EMmedian, EMca, and EMwmean, with final model selection based on predefined performance thresholds using True Skill Statistics ($TSS \geq 0.75$) as the primary criterion for model acceptance (Zhuo et al., 2020).

Variable importance was systematically assessed using a permutation-based approach implemented over 10 iterations, with confidence intervals established at 95% ($\alpha = 0.05$) to identify the most influential environmental predictors for each species. The weighted mean ensemble applied a proportional weight decay method to balance individual model contributions based on their performance metrics, ensuring that high-performing models contributed more heavily to final predictions while maintaining the benefits of ensemble uncertainty quantification.

5.2.5 Environmental variable selection and climate data

Environmental predictors were carefully selected based on ecological relevance to grassland bird species and their known habitat requirements. Nineteen bioclimatic variables along with elevation data were initially sourced from WorldClim (<https://www.worldclim.org/>), representing key climatic factors known to influence avian distribution patterns globally. To ensure statistical reliability and minimize multicollinearity among predictors, Pearson correlation coefficients were systematically computed for all variable pairs. Variables exhibiting correlation coefficients exceeding 0.7 were excluded from further analysis to prevent model overfitting and enhance interpretability (Murray et al., 2015).

Following rigorous selection based on ecological relevance, statistical independence, and correlation thresholds, five bioclimatic variables were identified as the

most influential factors affecting species distribution: Bio4 (temperature seasonality), Bio6 (minimum temperature of the coldest month), Bio7 (temperature annual range), Bio11 (mean temperature of the coldest quarter), and Bio17 (precipitation of the driest quarter). Additional ecologically significant predictor variables were incorporated directly into the modelling framework, including Distance to Grassland, Distance to Urban Areas, Normalized Difference Vegetation Index (NDVI), Distance to Water Bodies, and Elevation, providing a comprehensive representation of both climatic and landscape factors influencing species distribution patterns.

Future climate projections were derived from the Hadley Centre Global Environment Model (HadGEM3-GC31-LL) developed under the Coupled Model Intercomparison Project Phase 6 (CMIP6) framework (Andrews et al., 2020; Cavalcanti et al., 2022). Three Shared Socioeconomic Pathways (SSP) scenarios were incorporated to capture the range of possible climate futures: SSP1-2.6 (low-emission, sustainability-focused trajectory), SSP2-4.5 (moderate-emission, intermediate pathway), and SSP5-8.5 (high-emission, fossil-fuel-intensive scenario). Each scenario was analysed across four distinct temporal periods (2021-2040, 2041-2060, 2061-2080, and 2081-2100) to establish a comprehensive framework for evaluating long-term distributional changes under varying climate change trajectories.

5.2.6 Overlay analysis for population recovery site identification

To performed an overlay-based spatial analysis to identify potential population recovery sites by integrating future habitat suitability projections under multiple SSP's with primary habitat proximity metrics. Binary raster layers representing suitable/unsuitable habitat under each SSP scenario were prepared from prior species distribution modelling. A continuous raster of "Distance to Grassland" (in meters) was used as the primary habitat covariate, with smaller distances indicating higher suitability. SSP binary layers were stacked to calculate:

Consensus Proportion: the proportion of SSP scenarios predicting suitability for each pixel.

Weighted Suitability: a scenario-weighted overlay, with equal weights.

A binary consensus map was produced by applying a threshold of $\geq 50\%$ agreement across SSPs. The primary habitat filter was applied by retaining cells within 500 m of grassland. The weighted suitability surface was multiplied by a normalized inverse-distance surface to produce a final composite suitability score. Candidate recovery patches were delineated by thresholding the final suitability map (score ≥ 0.5) and applying an 8-neighbour clumping algorithm. Patches smaller than 1 ha (10,000 m²) were removed. For each remaining patch, mean suitability was calculated, and the top-ranked sites were identified. All outputs, including rasters, candidate patch shapefiles, and summary tables, were exported for further ecological interpretation.

5.2.7 Data processing and quality control

Prior to all spatial analyses, comprehensive data validation and curation procedures were implemented to enhance data quality and minimize potential biases that could affect model performance and conservation planning outcomes. All occurrence records were systematically examined to identify and eliminate duplicate entries, taxonomic misidentifications, and spatially imprecise records that could introduce uncertainty into distribution models. Records dated before 1970 were excluded from analyses to ensure temporal relevance and consistency with contemporary habitat conditions, while records lacking sufficient geographic precision were either improved through literature cross-referencing or excluded from the final dataset.

Spatial thinning techniques were systematically applied using methodologies described by Aiello-Lammens et al. (2015) to address potential spatial autocorrelation in occurrence data and ensure statistical independence among data points. A spatial filtering distance of 1 kilometers was applied to occurrence records, effectively reducing clustering effects while maintaining adequate sample sizes for robust model development. Following spatial refinement procedures, the final dataset was reduced to unique occurrence points. All analyses were conducted using R statistical software (version 4.5.1) with appropriate packages for spatial analysis, species distribution modelling, and statistical inference.

5.3 Results

The comprehensive data acquisition approach yielded substantial occurrence datasets for all three target species. Following the integration of primary field survey data with secondary sources from GBIF, eBird, and literature records, a total of 3,352 occurrence points were initially compiled across the three species. Jerdon's Babbler had the second-largest dataset with 1,006 occurrence points, while Black-breasted Parrotbill yielded the most extensive dataset of 1,723 points, and Marsh Babbler contributed 623 occurrence records.

After applying rigorous quality control procedures and spatial thinning protocols to reduce sampling bias and spatial autocorrelation, the final datasets comprised 233 high-quality occurrence points: 78 for Jerdon's Babbler, 104 for Black-breasted Parrotbill, and 51 for Marsh Babbler. These refined datasets formed the foundation for subsequent habitat suitability modelling and niche analysis, ensuring robust and spatially representative species distribution models for each target species.

5.3.1 Individual algorithm performance

Random Forest emerged as the consistently superior algorithm across all three species, achieving perfect or near-perfect sensitivity (99.97-100%) and exceptional specificity (99.91-99.99%) for Jerdon's Babbler, Black-breasted Parrotbill, and Marsh Babbler. Gradient Boosting Machine (GBM) and Multivariate Adaptive Regression Splines (MARS) demonstrated similarly robust performance, with GBM achieving sensitivity >99.4% and MARS >99.6% across species, validating the effectiveness of ensemble machine learning approaches for babbler species distribution modelling.

Traditional methods showed consistent limitations across species, with Surface Range Envelope (SRE) exhibiting the poorest performance in all cases (sensitivity: 65.19-80.33%, specificity: 99.44-100%). The performance hierarchy remained consistent: $RF \geq GBM \geq MARS > GAM > GLM > ANN > MAXNET > XGBOOST > CTA > FDA > MAXENT > SRE$, suggesting that algorithm selection patterns are transferable among ecologically similar species within the babbler guild.

5.3.2 Ensemble modelling outcomes

Ensemble modelling provided substantial improvements over individual algorithms across all species, with ensemble calibration approaching perfect discrimination (0.95-1.00). Ensemble approaches showed remarkable consistency, with sensitivity ranging 94.73-100 % and specificity 97.70-99.60% across the three species, indicating that ensemble modelling effectively minimizes species-specific algorithm biases and provides reliable projections for climate impact assessments.

The Ensemble Committee Approach (EMca) generally outperformed simple averaging methods, achieving optimal sensitivity-specificity balance with cutoff values of 587.56 to 697.72, suggesting that weighted ensemble approaches should be prioritized for conservation planning applications requiring high precision.

5.3.3 Current and future potential habitats of Jerdon's Babbler

The climate-elevation-only species distribution modelling approach yielded robust predictive performance across multiple machine learning algorithms for *Chrysomma altirostre*. Random Forest (RF) achieved the highest overall performance ($99.97 \pm 0.03\%$) and specificity ($99.91 \pm 0.01\%$), coupled with maximum ROC values (1.00 ± 0.00 for calibration, 0.99 ± 0.00 for validation), excellent TSS scores (1.00 ± 0.00 calibration, 0.76 ± 0.04 validation), and high KAPPA statistics (0.99 ± 0.00 calibration, 0.82 ± 0.03 validation). Gradient Boosting Machine (GBM) demonstrated exceptional calibration performance with sensitivity of $99.44 \pm 0.24\%$, specificity of $99.25 \pm 0.05\%$, and perfect calibration ROC values (1.00 ± 0.00).

Generalized Additive Models (GAM) showed strong performance with sensitivity of $94.32 \pm 1.15\%$, specificity of $94.67 \pm 0.31\%$, and excellent ROC values (0.99 ± 0.00 calibration, 0.99 ± 0.00 validation). Traditional methods demonstrated more variable results, with Surface Range Envelope (SRE) showing reduced sensitivity ($71.51 \pm 0.53\%$) but high specificity ($99.44 \pm 0.10\%$), and moderate ROC performance (0.85 ± 0.01 calibration, 0.80 ± 0.02 validation).

The constrained variable set (climate-elevation-only) resulted in generally lower validation metrics compared to full environmental models, with validation TSS scores

ranging from 0.59 ± 0.04 (SRE) to 0.90 ± 0.02 (GAM), reflecting the increased modelling challenge when excluding habitat and anthropogenic variables.

5.3.3.1 Importance of Environmental Variables

Elevation emerged as the dominant environmental determinant of Jerdon's Babbler distribution, demonstrating the highest mean variable importance (0.64 ± 0.01) across all algorithms (Table 9). This pattern reflects the species' adaptation to specific altitudinal zones within its range, consistent with its documented preference for low elevation grasslands. Grassland habitat showed substantial secondary importance (0.37 ± 0.01 mean importance), reinforcing the species' ecological specialization for open grassland habitats rather than forested environments.

Table 9 Variable importance scores across different algorithms for Jerdon's Babbler species distribution model

Variable	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXNET	RF	SRE	XGBOOST	Mean_VI	
Elevation	0.71 ± 0.01	0.66 ± 0.03	0.57 ± 0.02	0.87 ± 0.01	0.58 ± 0.01	0.73 ± 0.01	0.79 ± 0.01	0.83 0.01	± 0.01	0.21 ± 0.01	0.62 ± 0.01	0.53 ± 0.01	0.64 ± 0.01
Grassland	0.39 ± 0.01	0.42 ± 0.02	0.29 ± 0.00	0.44 ± 0.01	0.36 ± 0.01	0.38 ± 0.01	0.37 ± 0.01	0.35 0.01	± 0.00	0.09 ± 0.01	0.60 ± 0.01	0.24 ± 0.01	0.37 ± 0.01
Bio7	0.22 ± 0.02	0.31 ± 0.01	0.32 ± 0.01	0.70 ± 0.01	0.17 ± 0.00	0.40 ± 0.02	0.41 ± 0.03	0.28 0.01	± 0.00	0.04 ± 0.01	0.31 ± 0.01	0.23 ± 0.01	0.32 ± 0.01
Bio11	0.14 ± 0.02	0.03 ± 0.01	0.49 ± 0.03	0.89 ± 0.01	0.02 ± 0.00	0.44 ± 0.03	0.72 ± 0.02	0.24 0.03	± 0.00	0.04 ± 0.01	0.18 ± 0.01	0.05 ± 0.01	0.28 ± 0.01
Bio4	0.34 ± 0.02	0.03 ± 0.01	0.42 ± 0.03	0.76 ± 0.01	0.01 ± 0.00	0.53 ± 0.01	0.56 ± 0.03	0.26 0.02	± 0.00	0.01 ± 0.00	0.18 ± 0.00	0.00 ± 0.00	0.28 ± 0.01
Bio6	0.34 ± 0.03	0.06 ± 0.02	0.21 ± 0.04	0.24 ± 0.02	0.03 ± 0.01	0.54 ± 0.03	0.18 ± 0.04	0.47 0.03	± 0.00	0.03 ± 0.01	0.25 ± 0.01	0.02 ± 0.01	0.21 ± 0.01
NDVI	0.03 ± 0.01	0.03 ± 0.01	0.17 ± 0.01	0.21 ± 0.01	0.04 ± 0.00	0.25 ± 0.01	0.18 ± 0.02	0.15 0.01	± 0.00	0.04 ± 0.01	0.17 ± 0.01	0.07 ± 0.01	0.14 ± 0.00
Bio17	0.23 ± 0.02	0.14 ± 0.02	0.04 ± 0.01	0.01 ± 0.00	0.07 ± 0.00	0.11 ± 0.01	0.01 ± 0.00	0.02 0.00	± 0.00	0.09 ± 0.01	0.19 ± 0.01	0.14 ± 0.01	0.12 ± 0.01

Variable	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXNET	RF	SRE	XGBOOST	Mean_VI	
Urban	0.13	0.05	0.00	0.04	0.06	0.13	0.05 ± 0.01	0.04	±	0.01	0.35	0.01 ± 0.00	0.10 ± 0.00
	±	±	±	±	±	±				±			
	0.01	0.01	0.00	0.00	0.01	0.01				0.00	0.01		
Water	0.24	0.08	0.15	0.02	0.04	0.10	0.02 ± 0.00	0.02	±	0.06	0.01	0.10 ± 0.02	0.08 ± 0.00
	±	±	±	±	±	±				±			
	0.03	0.03	0.01	0.00	0.01	0.01				0.00	0.00		

Temperature seasonality variables ranked prominently, with Bio7 contributing 0.32 ± 0.01 importance, Bio11 showing 0.28 ± 0.01 importance, and Bio4 demonstrating 0.28 ± 0.01 importance. This temperature triad suggests that thermal stability and seasonal temperature patterns critically constrain distribution, potentially reflecting physiological limitations or seasonal resource requirements.

Cold tolerance indicators showed moderate influence, with Bio6 contributing 0.21 ± 0.01 importance, indicating that winter temperature thresholds may limit range expansion into higher elevations or more northern latitudes. Vegetation health (NDVI) contributed moderately (0.14 ± 0.00 importance), while precipitation (Bio17) and anthropogenic variables (Urban, Water) showed relatively minor influence (0.12 ± 0.01 , 0.10 ± 0.00 , and 0.08 ± 0.00 , respectively), suggesting that current distribution patterns are predominantly determined by topographic and thermal gradients rather than moisture availability.

5.3.3.2 Current Distribution and Habitat Extent

Jerdon's Babbler currently occupies 265,460.48 km² of climatically suitable habitat across eight South and Southeast Asian countries (Figure 18), representing one of the most extensive transboundary distributions among study species. India harbours the largest habitat extent (114,003.93 km², 42.9% of total habitat), establishing it as the core distribution centre for the species. Myanmar supports secondary habitat (47,511.80 km², 17.9%), followed closely by Bangladesh (45,865.75 km², 17.3%) and Pakistan (37,635.52 km², 14.2%).

Secondary range countries contribute smaller but potentially important populations: Nepal maintains 12,944.83 km² (4.9%), Vietnam supports 7,092.22 km² (2.7%), while Thailand and Bhutan harbour minimal habitat extents (243.86 km² and 162.57 km²,

respectively, each <0.1%). This distribution pattern reflects the species' adaptation to the extensive grassland and scrubland systems of the Indo-Gangetic plains and foothills.

5.3.3.3 *Climate Change Impacts*

All emission scenarios predict severe to catastrophic habitat contractions for Jerdon's Babbler, with vulnerability escalating dramatically under higher emission pathways and longer time horizons, threatening the species' persistence across most of its current range (Figure 19 and Figure 20).

5.3.3.3.1 **Low emission scenario (SSP1-2.6)**

Under the most conservative climate scenario, Jerdon's Babbler faces substantial immediate habitat reductions (Figure 20). The 2021-2040 period projects an 81.24% habitat loss, retaining only 49,787.81 km² of suitable area. Myanmar emerges as the most resilient country, experiencing a 59.92% loss while retaining 19,041.30 km² of habitat. India faces significant habitat reductions (81.75% loss, 20,809.27 km² remaining), while smaller range countries experience near-complete extirpation: Vietnam (96.56% loss), Pakistan (96.76% loss), and Nepal (93.09% loss). Bhutan faces complete habitat extirpation immediately.

Mid-century projections (2041-2060) intensify vulnerability, with total habitat losses reaching 90.29% (25,767.74 km² remaining). Myanmar maintains relative stability (78.79% loss, 10,079.49 km² remaining) while India experiences accelerated degradation (89.50% loss, 11,969.40 km²). Thailand and Bhutan achieve complete extirpation, with other countries showing progressive deterioration.

Late-century trends (2061-2080, 2081-2100) demonstrate continued habitat erosion, with losses stabilizing around 91-94%. Myanmar and India persist as the primary refugia, though with severely contracted ranges. Vietnam and Thailand face complete extirpation by century's end, highlighting the particular vulnerability of peripheral populations.

5.3.3.3.2 Moderate emission scenario (SSP2-4.5)

The moderate emission pathway reveals accelerating habitat degradation with threshold effects. Initial impacts (84.70% loss by 2021-2040, 40,602.47 km² remaining) escalate rapidly through mid-century, reaching 92.54% loss by 2041-2060 (19,813.51 km²). Catastrophic habitat collapse occurs by 2061-2080, with 96.96% total loss leaving only 8,067.65 km² regionally.

Country-level vulnerability follows consistent patterns: Myanmar and India emerge as the sole long-term refugia, with Myanmar retaining 2,885.66-3,332.74 km² and India maintaining 4,328.49-4,755.24 km² by century's end. All other countries face complete or near-complete extirpation, with Vietnam, Thailand, Nepal, and Bhutan achieving zero suitable habitat by 2041-2080, and Pakistan, Bangladesh reduced to minimal remnants.

5.3.3.3.3 High emission scenario (SSP5-8.5)

The high emission scenario produces the most devastating habitat projections, with initial losses of 83.40% by 2021-2040 (44,057.14 km² remaining) accelerating to 94.71% by 2041-2060 (14,042.20 km²). Near-complete regional extirpation occurs by 2061-2080 with 99.14% habitat loss (2,276.01 km²), culminating in 99.94% total habitat loss by 2081-2100 (162.57 km² remaining).

Regional extirpation patterns intensify dramatically: Pakistan, Nepal, Vietnam, Thailand, and Bhutan achieve complete extirpation by 2041-2061. Bangladesh faces complete extirpation by century's end, while Myanmar and India persist with minimal remnant populations - Myanmar retaining 121.93 km² (99.74% loss) and India maintaining 40.64 km² (99.96% loss) by 2081-2100.

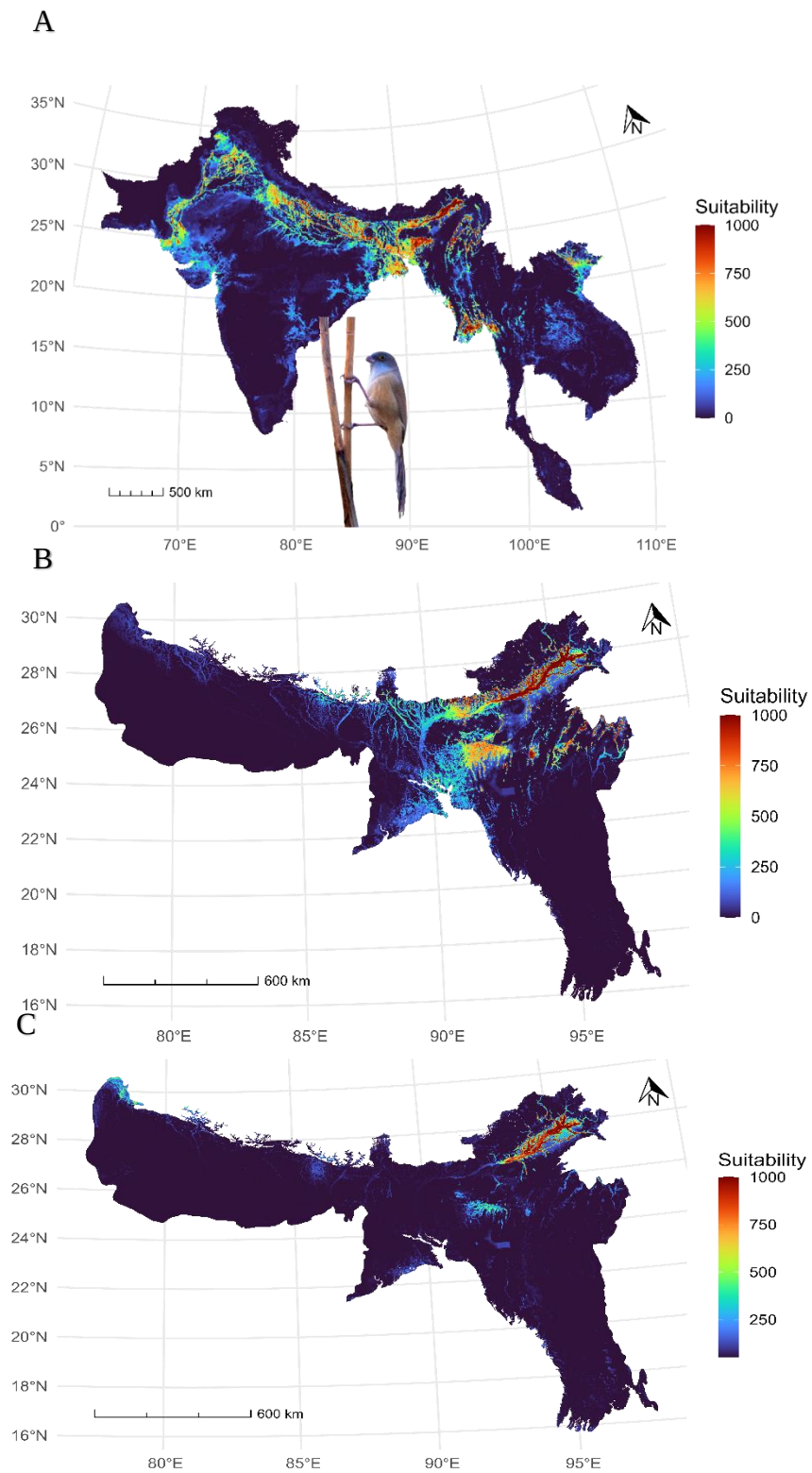


Figure 18 Ecological Niche Models of the Current Distribution:
A – Jerdon's Babbler, B – Black-breasted Parrotbill, C – Marsh Babbler

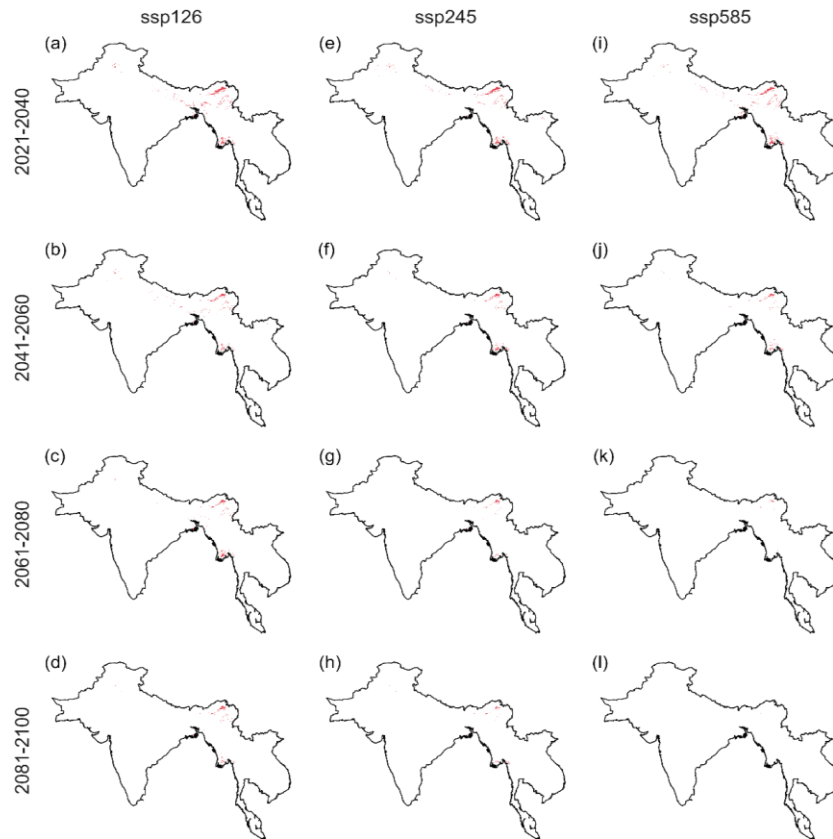


Figure 19 Distribution of Jerdon's Babbler Across Different SSP Scenarios and Time Periods

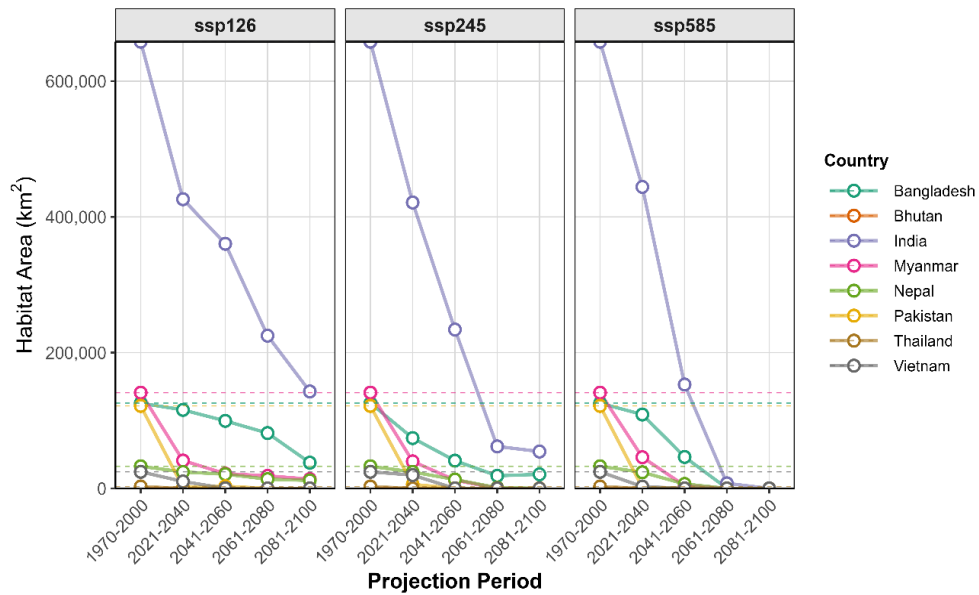


Figure 20 Effects of Climate Change on Jerdon's Babbler's Habitat Area under Varying Future Projections

5.3.4 Current and future potential habitats of Black-breasted Parrotbill

Random Forest (RF) achieved the highest performance metrics with perfect sensitivity ($100.00 \pm 0.00\%$) and specificity ($99.99 \pm 0.00\%$), alongside maximum ROC values (1.00 ± 0.00 for both calibration and validation), TSS values (1.00 ± 0.00 calibration, 0.91 ± 0.02 validation), and KAPPA statistics (1.00 ± 0.00 calibration, 0.93 ± 0.01 validation). Gradient Boosting Machine (GBM) and Multivariate Adaptive Regression Splines (MARS) also demonstrated superior performance, with GBM achieving sensitivity of $99.65 \pm 0.16\%$ and specificity of $99.72 \pm 0.02\%$, while MARS recorded sensitivity of $99.67 \pm 0.16\%$ and specificity of $99.28 \pm 0.08\%$. Traditional methods showed variable effectiveness, with Surface Range Envelope (SRE) exhibiting the poorest performance (sensitivity: $65.19 \pm 0.51\%$, specificity: $100.00 \pm 0.00\%$, ROC: 0.83 ± 0.00 calibration, 0.77 ± 0.02 validation).

5.3.4.1 Importance of Environmental Variables

Temperature-related variables emerged as the primary drivers of black-breasted parrotbill distribution. Bio6 demonstrated the highest mean variable importance (0.42 ± 0.01), followed by Bio7 with 0.41 ± 0.01 importance. Grassland habitat showed substantial influence (0.35 ± 0.00 mean importance) (Table 10).

Table 10 Variable importance scores across different algorithms for Black Breasted Parrotbill Babbler species distribution model

Variable	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF	SRE	XGBOOST	Mean_VI
Bio6	0.57 ± 0.05	0.29 ± 0.01	0.68 ± 0.02	0.86 ± 0.00	0.06 ± 0.01	0.62 ± 0.03	0.60 ± 0.02	0.11 ± 0.01	0.03 ± 0.00	0.45 ± 0.01	0.04 ± 0.01	0.42 ± 0.01
Bio7	0.61 ± 0.05	0.08 ± 0.02	0.47 ± 0.03	0.84 ± 0.01	0.06 ± 0.01	0.47 ± 0.03	0.67 ± 0.02	0.14 ± 0.01	0.06 ± 0.00	0.51 ± 0.01	0.35 ± 0.01	0.41 ± 0.01
Grassland	0.39 ± 0.01	0.46 ± 0.01	0.23 ± 0.01	0.37 ± 0.01	0.41 ± 0.01	0.40 ± 0.02	0.36 ± 0.02	0.37 ± 0.01	0.13 ± 0.00	0.37 ± 0.01	0.37 ± 0.01	0.35 ± 0.00
Bio11	0.47 ± 0.04	0.16 ± 0.02	0.40 ± 0.03	0.41 ± 0.02	0.04 ± 0.00	0.72 ± 0.02	0.27 ± 0.04	0.15 ± 0.01	0.04 ± 0.00	0.47 ± 0.01	0.05 ± 0.01	0.29 ± 0.01

Variable	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF	SRE	XGBOOST	Mean_VI
Elevation	0.24 ± 0.02	0.07 ± 0.02	0.26 ± 0.02	0.55 ± 0.01	0.01 ± 0.00	0.56 ± 0.02	0.41 ± 0.02	0.13 ± 0.01	0.03 ± 0.00	0.22 ± 0.01	0.02 ± 0.00	0.24 ± 0.01
Bio17	0.32 ± 0.05	0.61 ± 0.02	0.13 ± 0.01	0.01 ± 0.00	0.50 ± 0.01	0.11 ± 0.01	0.06 ± 0.01	0.17 ± 0.01	0.10 ± 0.00	0.49 ± 0.01	0.14 ± 0.01	0.23 ± 0.01
Bio4	0.56 ± 0.03	0.13 ± 0.02	0.12 ± 0.02	0.14 ± 0.02	0.03 ± 0.01	0.53 ± 0.03	0.16 ± 0.03	0.18 ± 0.01	0.02 ± 0.00	0.52 ± 0.01	0.05 ± 0.01	0.21 ± 0.01
Urban	0.05 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.00	0.01 ± 0.00	0.05 ± 0.00	0.03 ± 0.01	0.07 ± 0.00	0.01 ± 0.00	0.22 ± 0.01	0.00 ± 0.00	0.04 ± 0.00
NDVI	0.01 ± 0.00	0.01 ± 0.01	0.02 ± 0.00	0.03 ± 0.00	0.00 ± 0.00	0.06 ± 0.01	0.04 ± 0.01	0.09 ± 0.00	0.01 ± 0.00	0.10 ± 0.00	0.00 ± 0.00	0.03 ± 0.00
Water	0.03 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.03 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.01 ± 0.00

Bio11 ranked fourth in importance (0.29 ± 0.01), while elevation contributed moderately (0.24 ± 0.01), indicating the species' association with specific altitudinal zones. Bio17 and Bio4 showed moderate importance (0.23 ± 0.01 and 0.21 ± 0.01 , respectively), suggesting sensitivity to seasonal climatic variations. Notably, anthropogenic variables (Urban: 0.04 ± 0.00) and vegetation indices (NDVI: 0.03 ± 0.00) showed minimal influence, indicating the species' current distribution is primarily constrained by natural climatic factors.

5.3.4.2 Current Distribution and Habitat Extent

The current suitable habitat for Black-breasted parrotbill spans 69,506.08 km² across seven northeastern Indian states. Assam harbours the largest habitat extent (45,842.32 km², 65.9% of total habitat), followed by Arunachal Pradesh (9,838.67 km², 14.2%) and Nagaland (5,334.75 km², 7.7%). The remaining states: Manipur, Nagaland, Tripura, Mizoram, and Meghalaya, collectively account for 12.2% of the total habitat, with individual extents ranging from 1,082.46 km² to 3,461.81 km².

5.3.4.3 Climate Change Impacts

All climate change scenarios predict severe habitat contractions for the black-breasted parrotbill, with the magnitude and timing varying significantly among SSP pathways and time periods (Figure 18).

5.3.4.3.1 Low emission scenario (SSP1-2.6)

Under the most optimistic climate scenario, habitat losses remain substantial throughout the 21st century (Figure 21). By 2021-2040, suitable habitat is projected to decline by 70.58% to 20,451.20 km². Arunachal Pradesh emerges as the primary refugium, retaining 6,877.73 km² (66.6% of remaining habitat), while experiencing only a 30.09% reduction from current levels. Assam faces a 71.74% habitat loss, retaining 12,956.28 km² (Figure 22). Complete habitat extirpation is projected for Mizoram, Manipur, and Tripura by 2021-2040.

Habitat degradation intensifies through the century under SSP1-2.6, with 2081-2100 projections showing 79.31% total habitat loss (14,382.95 km² remaining). Arunachal Pradesh continues as the most stable refuge (7,234.60 km², 26.47% loss), while Assam retains 6,779.62 km² (85.21% loss). Nagaland shows marginal recovery in later periods, maintaining 368.73 km² by century's end.

5.3.4.3.2 Moderate emission scenario (SSP2-4.5)

The moderate emission scenario demonstrates non-linear habitat decline patterns. Initially showing better outcomes than SSP1-2.6 in early periods (54.86% loss by 2021-2040, retaining 31,373.93 km²), the trajectory rapidly deteriorates in subsequent decades. By 2041-2060, habitat collapse accelerates to 92.04% loss (5,535.74 km² remaining), with near-complete extirpation by 2061-2080 (99.91% loss, 61.72 km² remaining). Complete regional extirpation occurs by 2081-2100, with only 0.79 km² remaining in Arunachal Pradesh.

5.3.4.3.3 High emission scenario (SSP5-8.5)

The high emission scenario produces the most catastrophic outcomes, with habitat losses of 76.83% by 2021-2040 (16,103.96 km² remaining), escalating to 99.69% loss by 2041-2060 (212.06 km²). Complete regional extirpation occurs by 2061-2080, with zero suitable habitat projected across all northeastern Indian states through 2081-2100.

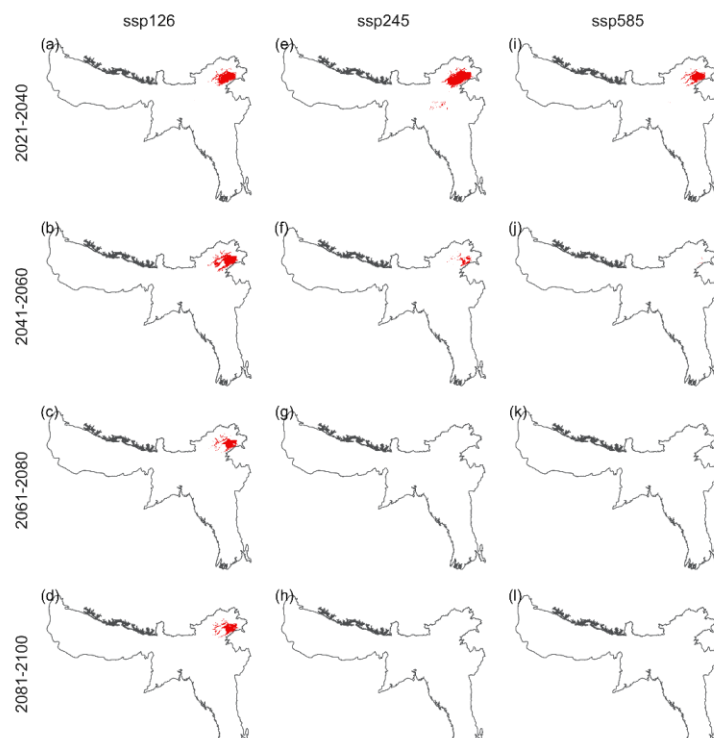


Figure 21 Distribution of Black-breasted Parrotbill across different SSP scenarios and time periods

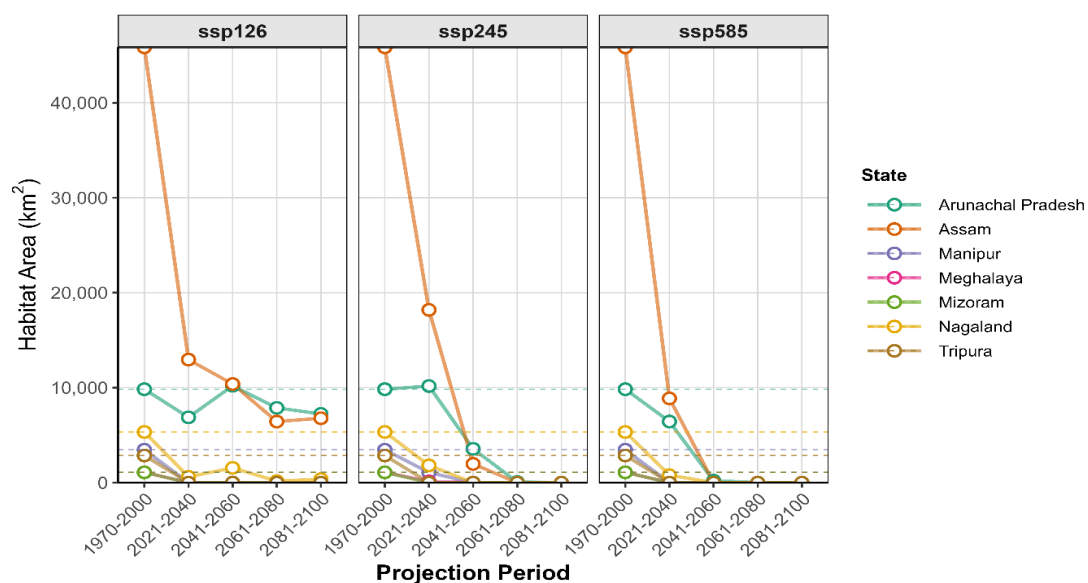


Figure 22 Effects of climate change on Black-breasted Parrotbill's habitat area under varying future projections

5.3.5 Current and future potential habitats of Marsh Babbler

Multivariate Adaptive Regression Splines (MARS) demonstrated the highest overall performance with exceptional sensitivity ($99.92 \pm 0.08\%$) and specificity ($99.74 \pm 0.05\%$), coupled with perfect ROC values (1.00 ± 0.00 for calibration, 0.98 ± 0.01 for validation), TSS scores (1.00 ± 0.00 calibration, 0.93 ± 0.02 validation), and KAPPA statistics (0.98 ± 0.01 calibration, 0.92 ± 0.02 validation). Random Forest (RF) also achieved exceptional accuracy with perfect sensitivity ($100.00 \pm 0.00\%$), high specificity ($99.94 \pm 0.01\%$), and maximum ROC values (1.00 ± 0.00 for both calibration and validation).

Generalized Additive Models (GAM) and Artificial Neural Networks (ANN) showed excellent performance, with GAM recording sensitivity of $99.88 \pm 0.12\%$ and ANN achieving $99.65 \pm 0.15\%$ sensitivity. Traditional approaches demonstrated more variable results, with Surface Range Envelope (SRE) showing the poorest calibration performance (sensitivity: $68.71 \pm 1.14\%$, ROC: 0.84 ± 0.01), though achieving high specificity ($99.95 \pm 0.01\%$).

5.3.5.1 Importance of Environmental Variables

Precipitation-related variables emerged as the dominant environmental drivers of Marsh Babbler distribution patterns (Table 11). Bio17 demonstrated the highest mean variable importance (0.49 ± 0.01), reflecting the species' dependence on consistent moisture availability throughout the year. Grassland habitat showed substantial secondary importance (0.33 ± 0.01 mean importance), indicating the species' preference for open wetland and grassland-marsh interfaces characteristic of its ecological niche.

**Table 11 Variable importance scores across different algorithms for marsh Babbler
Babbler species distribution model**

Variable	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXNET	RF	SRE	XGBOOST	Mean_VI
Bio17	0.64	0.71	0.92	0.12	0.71	0.15	0.45 ± 0.04	0.19 ± 0.02	0.13	0.60	0.65 ± 0.02	0.49 ± 0.01
	±	±	±	±	±	±			±	±		
	0.02	0.02	0.01	0.01	0.01	0.01			0.00	0.01		
Grassland	0.31	0.52	0.03	0.51	0.29	0.32	0.40 ± 0.03	0.38 ± 0.01	0.08	0.53	0.32 ± 0.02	0.33 ± 0.01
	±	±	±	±	±	±			±	±		
	0.02	0.03	0.00	0.03	0.02	0.02			0.00	0.01		
Bio7	0.12	0.00	0.07	0.78	0.00	0.72	0.07 ± 0.02	0.45 ± 0.03	0.03	0.55	0.00 ± 0.00	0.24 ± 0.01
	±	±	±	±	±	±			±	±		
	0.02	0.00	0.02	0.03	0.00	0.02			0.00	0.01		
Bio4	0.12	0.08	0.03	0.70	0.00	0.67	0.24 ± 0.04	0.14 ± 0.02	0.02	0.60	0.02 ± 0.00	0.22 ± 0.01
	±	±	±	±	±	±			±	±		
	0.01	0.02	0.01	0.03	0.00	0.03			0.00	0.01		
Bio6	0.02	0.00	0.19	0.69	0.00	0.76	0.05 ± 0.03	0.29 ± 0.02	0.01	0.44	0.00 ± 0.00	0.21 ± 0.01
	±	±	±	±	±	±			±	±		
	0.00	0.00	0.02	0.03	0.00	0.02			0.00	0.01		
Bio11	0.03	0.01	0.23	0.56	0.00	0.58	0.05 ± 0.03	0.00 ± 0.00	0.01	0.39	0.00 ± 0.00	0.16 ± 0.01
	±	±	±	±	±	±			±	±		
	0.01	0.00	0.02	0.03	0.00	0.02			0.00	0.01		
Elevation	0.23	0.00	0.05	0.34	0.01	0.23	0.25 ± 0.02	0.26 ± 0.01	0.01	0.34	0.01 ± 0.00	0.15 ± 0.01
	±	±	±	±	±	±			±	±		
	0.01	0.00	0.01	0.02	0.00	0.01			0.00	0.01		
NDVI	0.00	0.09	0.01	0.08	0.00	0.08	0.11 ± 0.01	0.00 ± 0.00	0.00	0.15	0.00 ± 0.00	0.05 ± 0.00
	±	±	±	±	±	±			±	±		
	0.00	0.02	0.00	0.01	0.00	0.01			0.00	0.01		
Urban	0.11	0.00	0.02	0.06	0.00	0.08	0.06 ± 0.01	0.01 ± 0.00	0.00	0.15	0.00 ± 0.00	0.05 ± 0.00
	±	±	±	±	±	±			±	±		
	0.01	0.00	0.00	0.01	0.00	0.01			0.00	0.01		
Water	0.06	0.04	0.00	0.04	0.01	0.14	0.00 ± 0.00	0.00 ± 0.00	0.01	0.02	0.01 ± 0.00	0.04 ± 0.00
	±	±	±	±	±	±			±	±		
	0.00	0.01	0.00	0.01	0.00	0.01			0.00	0.00		

Temperature seasonality variables ranked prominently, with Bio7 contributing 0.24 ± 0.01 importance and Bio4 showing 0.22 ± 0.01 importance. Cold tolerance emerged as a significant constraint, with Bio6 and Bio11 showing moderate importance (0.21 ± 0.01 and 0.16 ± 0.01 , respectively). Elevation contributed moderately (0.15 ± 0.01), suggesting preferences within the species' lowline wetland habitats.

Anthropogenic and vegetation variables showed minimal influence on current distribution patterns, with both Urban development and NDVI contributing only 0.05 ± 0.00 importance each, while Water proximity registered 0.04 ± 0.00 importance. This pattern suggests that natural climatic gradients and precipitation regimes predominantly determine suitable habitat, with limited current influence from human landscape modifications.

5.3.5.2 Current Distribution and Habitat Extent

The Marsh Babbler currently occupies 885,166.37 km² of suitable habitat across three northeastern Indian states, representing one of the more extensive habitat ranges among regional endemic species. Assam harbours the vast majority of suitable habitat (670,448.80 km², 75.7% of total habitat), establishing it as the core distribution centre for the species. Arunachal Pradesh supports substantial secondary habitat (185,759.35 km², 21.0%), while Nagaland maintains a smaller population (28,958.22 km², 3.3%). The species' current distribution pattern reflects its specialization for Grasslands and marsh habitats concentrated in the Eastern Himalayan region.

5.3.5.3 Climate Change Impacts

All emission scenarios predict substantial to severe habitat contractions for the Marsh Babbler like other species discussed, with vulnerability patterns varying significantly among states and intensifying with higher emission pathways and longer time horizons (Figure 18).

5.3.5.3.1 Low Emission Scenario (SSP1-2.6)

Under the most conservative climate scenario, the Marsh Babbler faces significant but manageable habitat reductions (Figure 23). The 2021-2040 period projects a 71.50% habitat loss, retaining 252,292.12 km² of suitable area. Nagaland experiences complete habitat extirpation immediately, while Assam and Arunachal Pradesh show parallel vulnerability patterns with approximately 70% habitat losses (70.60% and 70.31%, respectively).

Mid-century projections (2041-2060) show unexpected habitat recovery, with total losses decreasing to 47.55% and 464,266.27 km² remaining suitable habitat (Figure 24). This improvement reflects Nagaland's partial habitat recovery (95.30% loss compared to complete extirpation) and reduced losses in Assam and Arunachal Pradesh (46.19% and 45.02%, respectively). Late-century trends (2061-2080, 2081-2100) demonstrate non-linear dynamics, with habitat losses fluctuating between 49.27% and 68.06%, suggesting complex interactions between climatic variables and habitat suitability thresholds.

5.3.5.3.2 **Moderate emission scenario (SSP2-4.5)**

The moderate emission pathway reveals accelerating habitat degradation through the 21st century. Initial impacts appear less severe than SSP1-2.6 (46.44% loss by 2021-2040, retaining 474,081.59 km²), but vulnerability escalates dramatically in subsequent decades. By 2041-2060, habitat losses reach 86.51% (119,368.82 km² remaining), with near-complete regional collapse by 2061-2080 (96.04% loss, 35,095.33 km² remaining).

Nagaland faces consistent complete extirpation across all time periods under SSP2-4.5, while Arunachal Pradesh experiences progressive degradation from manageable losses (43.20% by 2021-2040) to near-complete extirpation (99.86% by 2061-2080). Assam maintains relative resilience but still faces severe contractions, with habitat losses ranging from 45.31% to 94.80% across time periods.

5.3.5.3.3 **High emission scenario (SSP5-8.5)**

The high emission scenario produces the most catastrophic habitat projections. Initial habitat losses of 72.85% by 2021-2040 (240,343.05 km² remaining) accelerate to 94.85% by 2041-2060 (45,601.58 km²). Near-complete regional extirpation occurs by 2061-2080 with 97.61% habitat loss (21,154.74 km²), culminating in 98.49% total habitat loss by 2081-2100 (13,351.26 km² remaining).

State-level vulnerability follows consistent patterns, with Nagaland facing immediate near-complete to complete extirpation across all time periods. Arunachal Pradesh experiences progressive collapse, from 72.08% loss initially to 99.80% loss by century's end. Assam emerges as the sole long-term refugium, retaining 12,985.47 km² (98.06% loss) by 2081-2100, representing the species' last viable habitat under extreme climate scenarios.

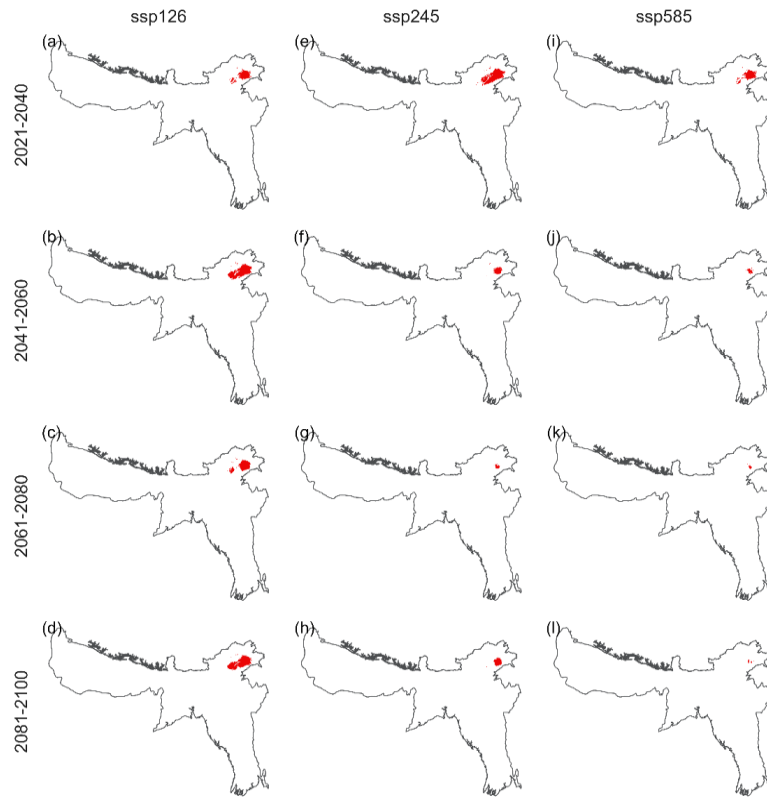


Figure 23 Distribution of Marsh Babbler across different SSP scenarios and time periods

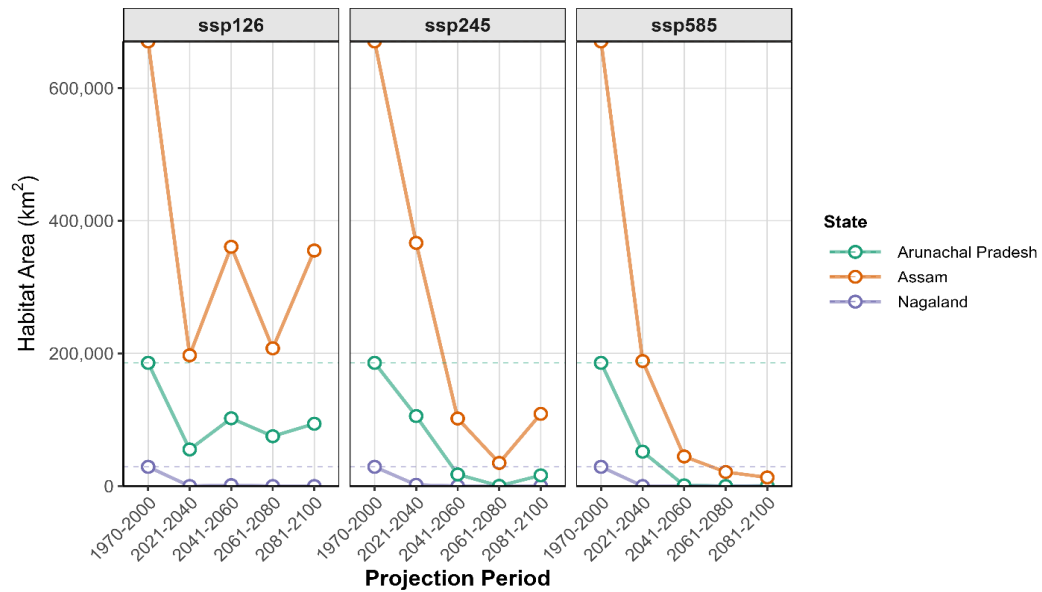


Figure 24 Effects of climate change on Marsh Babbler's habitat area under varying future projections

5.3.6 Climate refugia

5.3.6.1 Spatial Distribution of Climate Refugia

The ensemble climate refugia analysis identified 6,161.935 km² of critical refuge habitat across two northeastern Indian states, representing areas projected to remain climatically suitable for one or more target species under future climate scenarios (Figure 25, Figure 26 and Figure 27). Assam emerges as the dominant refugia state, harbouring 4,745.798 km² (77.0% of total refuge area), while Arunachal Pradesh contains 1,416.137 km² (23.0% of total refuge area).

5.3.6.2 Multi-species Refuge Overlap Patterns

Two-species overlap zones represent the most extensive refuge category, comprising 4,096.4 km² (66.5% of total refuge area) across both states. In Assam, two-species overlap areas cover 3,114.4 km² (65.6% of state refuge area), while Arunachal Pradesh contains 982 km² (69.3% of state refuge area) (Table 12). This pattern indicates substantial spatial congruence in climate requirements among the target babbler species, suggesting that conservation investments in these overlap zones could provide synergistic benefits for multiple species simultaneously.

Table 12 Area (km²) and percentage of climatic refuge categories by state

State	1 Species Only	2 Species Overlap	3 Species Overlap	Total Area (km ²)
Arunachal Pradesh	338 (23.9%)	982 (69.3%)	96.2 (6.8%)	1,416.137
Assam	1080 (22.8%)	3114.4 (65.6%)	551.4 (11.6%)	4,745.798

Three-species overlap zones (Figure 28), representing the highest conservation priority areas, cover 647.6 km² (10.5% of total refuge area). Assam contains the vast majority of three-species refugia (551.4 km², 11.6% of state refuge area), compared to 96.2 km² (6.8% of state refuge area) in Arunachal Pradesh. These core refugia areas represent irreplaceable climate adaptation zones where all three species are projected to persist under future climate scenarios, making them critical targets for immediate conservation action and protected area expansion.

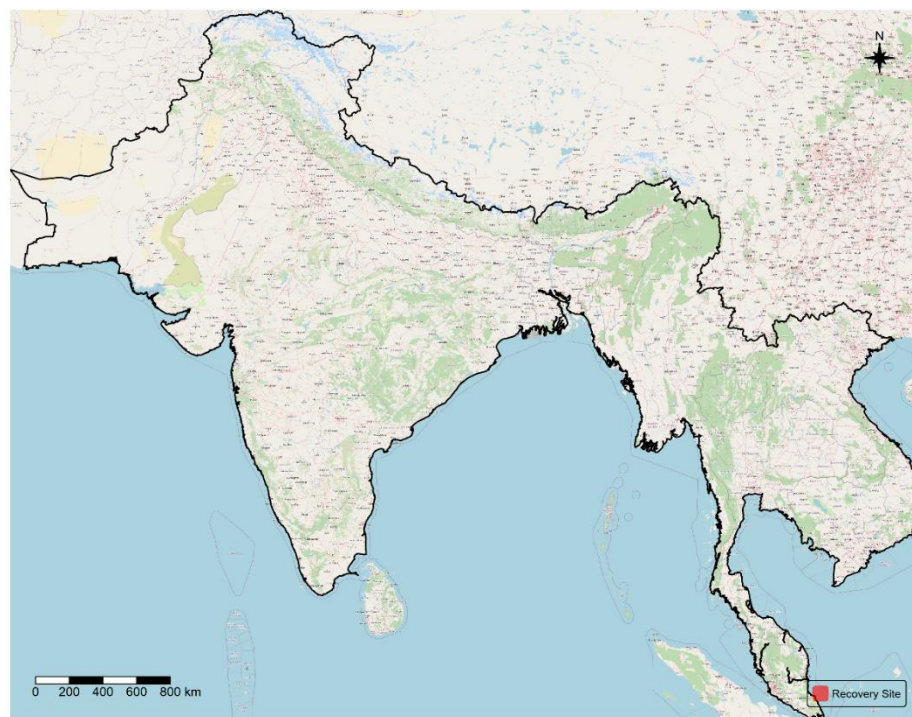


Figure 25 Potential recovery sites identified for Jerdon's Babbler



Figure 26 Potential recovery or refuge sites identified for Black-breasted Parrotbill



Figure 27 Potential recovery or refuge sites identified for Marsh Babbler

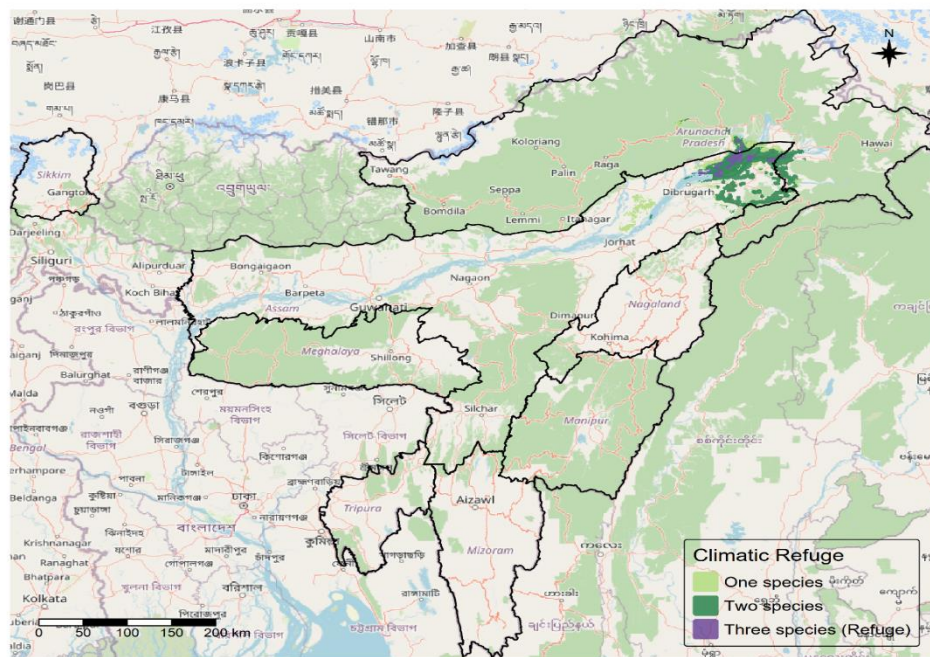


Figure 28 Combined potential refuges for all three study species under climate-induced habitat shifts across SSP scenarios

5.4 Discussion

5.4.1 Algorithm performance and methodological implications

Random Forest consistently emerged as the superior modelling algorithm across all three grassland bird species, achieving near-perfect sensitivity (99.97-100.00%) and specificity (99.91-99.99%) values. This finding aligns with recent comparative studies demonstrating Random Forest's robustness for species distribution modelling, particularly for cryptic species with limited occurrence data (Valavi et al., 2021). The exceptional performance of ensemble methods, with calibration values approaching near-perfect discrimination (0.95–1.00), underscores the robustness of the BIOMOD2 framework in mitigating methodological uncertainties that often arise from reliance on single-algorithm approaches (Thuiller et al., 2009). This result is consistent with previous findings demonstrating that ensemble forecasting improves predictive accuracy and reduces algorithm-specific biases in ecological niche and species distribution modelling (Hao et al., 2019). Traditional methods, particularly Surface Range Envelope (SRE), consistently showed the poorest performance across species (sensitivity: 65.19-80.33%), reinforcing the superiority of machine learning approaches for grassland bird conservation planning.

5.4.2 Environmental drivers of species distribution

Elevation emerged as the dominant environmental determinant for Jerdon's Babbler distribution (0.64 ± 0.01 mean importance), reflecting the species' adaptation to specific altitudinal zones within the Indo-Gangetic plains and foothills. Temperature-related variables, particularly Bio6 (minimum temperature of coldest month) and Bio7 (temperature annual range), proved critical for Black-breasted Parrotbill (0.42 ± 0.01 and 0.41 ± 0.01 importance respectively) and Marsh Babbler distributions. The dominance of precipitation-related variables, particularly Bio17 (precipitation of driest quarter), reveals the fundamental importance of year-round moisture availability for Marsh Babbler persistence. This finding aligns with the species' ecological specialization for marshy habitats where consistent water availability is critical for prey abundance and nesting success (Grimmett, et al., 2016).

The secondary importance of grassland habitats across all focal species (mean importance = 0.35–0.37) reinforces their ecological specialization for open grassland ecosystems rather than forested environments (Thapa et al., 2015). Precipitation variables, particularly Bio17 (precipitation of the driest quarter), showed the highest contribution for Marsh Babbler (*Pellorneum palustre*) (0.49 ± 0.01), highlighting this species' dependence on consistent moisture availability throughout the year. This finding is consistent with earlier ecological assessments that describe the species' reliance on seasonally inundated grasslands and marsh habitats (BirdLife International, 2024b). Such hydrological dependence underscores the vulnerability of grassland specialists like Marsh Babbler and Jerdon's Babbler to climate-driven changes in precipitation regimes (Parengal et al., 2025).

5.4.3 Magnitude and patterns of climate-induced habitat loss

All three species face catastrophic habitat contractions under projected climate scenarios, with vulnerability escalating dramatically under higher emission pathways. Jerdon's Babbler, despite having the most extensive current range (265,460.48 km²), faces immediate losses of 81-84% by 2021-2040 across all scenarios, escalating to near-complete extirpation (99.94% loss) under SSP5-8.5 by century's end. Black-breasted Parrotbill shows similarly devastating projections, with complete regional extirpation occurring by 2061-2080 under the high emission scenario. These projected losses exceed those reported for other grassland bird species globally, highlighting the particular vulnerability of Asian grassland specialists to climate change (Bateman et al., 2020). The non-linear habitat decline patterns observed, particularly under SSP2-4.5 scenarios, suggest complex threshold effects where moderate warming triggers disproportionate habitat collapse.

The projected habitat contractions across all emission scenarios represent one of the most severe climate vulnerabilities documented among Asian grassland birds. The 81-99% habitat losses projected by century's end indicate that Jerdon's Babbler faces potential functional extinction across most of its current range, with cascading implications for South Asian grassland biodiversity conservation (Şekercioğlu et al., 2012).

These findings support the urgent need for climate-smart conservation strategies, including habitat corridor establishment and protected area expansion in climatically stable

refugia, as recommended by (Rana et al., 2025) for grassland restoration under climate change.

5.4.4 Geographic patterns of species vulnerability

Myanmar and India emerge as the primary long-term refugia for Jerdon's Babbler, with Myanmar showing relative resilience (59.92-78.79% habitat loss) compared to other range countries. Complete extirpation is projected for peripheral populations in Vietnam, Thailand, Nepal, and Bhutan by mid-century under most scenarios, reflecting the particular vulnerability of range-edge populations to climate change. For the regionally endemic Black-breasted Parrotbill and Marsh Babbler, Arunachal Pradesh and Assam represent the sole potential refugia, with Arunachal Pradesh showing greater climate resilience for Black-breasted Parrotbill. These geographic vulnerability patterns align with global studies demonstrating that species at higher latitudes and elevations may have greater climate adaptation potential (Dantas-Queiroz et al., 2021).

5.4.5 Climate refugia and multi-species conservation opportunities

The identification of 6,161.935 km² of critical refuge habitat, with 66.5% comprising two-species overlap zones, provides strategic opportunities for synergistic conservation investments. Three-species overlap zones covering 647.6 km² represent the highest conservation priority areas, with Assam harbouring 85% of these core refugia. This spatial congruence in climate requirements among target species suggests that landscape-scale conservation approaches may be more efficient than single-species strategies. The predominance of multi-species refugia supports systematic conservation planning approaches that maximize conservation benefits across multiple threatened taxa simultaneously (Kumar et al., 2021).

5.4.6 Conservation implications and adaptive management

The severe habitat projections underscore the urgent need for both climate adaptation and mitigation strategies to improve species resilience. Protected area expansion should prioritize identified three-species refugia in Assam and Arunachal Pradesh, where 647.6 km² of core habitat requires immediate conservation action. Ex-situ conservation measures, including captive breeding programs, may be necessary for Black-breasted

Parrotbill given its projected complete extirpation under high emission scenarios. Habitat restoration efforts should focus on enhancing connectivity between refugia areas to facilitate climate-mediated range shifts. The dramatic differences in outcomes between emission scenarios (81% vs 99.94% habitat loss for Jerdon's Babbler) emphasize that global climate mitigation remains essential for grassland bird conservation.

5.4.7 Limitations and future research directions

The ensemble modelling approach employed in this study represents current best practices in species distribution modelling, as established by Araújo & New, (2007) and Thuiller et al., (2009). The integration of 12 different algorithms provides robust consensus predictions while accounting for methodological uncertainty inherent in individual modelling approaches. Several limitations may affect the precision of habitat projections, including the use of single climate model projections (HadGEM3-GC31-LL) rather than multi-model ensembles, which could improve uncertainty quantification. The exclusion of land-use change scenarios from future projections may underestimate actual habitat loss, particularly given the rapid grassland conversion rates in the study region. Future research should integrate anthropogenic pressures, including agricultural expansion and urbanization, with climate projections to provide more comprehensive habitat assessments. Long-term demographic monitoring within identified refugia areas is essential to validate model predictions and inform adaptive management strategies. Additionally, incorporating species-specific dispersal capabilities and genetic diversity assessments would enhance the biological realism of range shift projections.

The findings demonstrate that Asian grassland birds face unprecedented climate-induced habitat loss, requiring immediate conservation action focused on identified refugia areas and integrated climate adaptation strategies. The methodological framework developed here provides a robust foundation for expanding similar assessments to other threatened grassland taxa across the region.

Chapter 6

CHAPTER 6

SYNTHESIS AND CONSERVATION IMPLICATIONS

6.1 Key Findings

This comprehensive assessment of three threatened grassland bird species in the Brahmaputra floodplains represents the first systematic investigation of their habitat requirements, threat vulnerabilities, and climate change responses using ensemble species distribution modelling approaches. The research reveals that Jerdon's Babbler (*Chrysomma altirostre*), Black-breasted Parrotbill (*Paradoxornis flavirostris*), and Marsh Babbler (*Pellorneum palustre*) exhibit distinct yet overlapping ecological specializations that reflect their evolutionary adaptations to the dynamic floodplain ecosystem, while simultaneously facing unprecedented conservation challenges that threaten their long-term persistence across the region.

6.1.1 Species exhibits highly specialized ecological requirements

The habitat characterization analysis demonstrated that each species exhibits highly specialized ecological requirements within the broader grassland matrix, with implications for both current conservation planning and future climate adaptation strategies.

Jerdon's Babbler emerged as the most habitat-specialized species, showing an overwhelming dependence on *Saccharum* grasslands with exceptionally strong statistical associations between species presence and *Saccharum* height ($\beta = 0.314$, $z = 9.64$, $p < 0.001$) combined with highly significant negative relationships with distance to *Saccharum* patches ($\beta = -0.389$, $z = -4.73$, $p < 0.001$), confirming the species' absolute requirement for proximity to tall *Saccharum* stands (Parengal et al., 2025). This finding aligns with previous documentation of the species' preference for dense, contiguous grasslands dominated by specific tall grass species, emphasizing the critical importance of maintaining large-scale *Saccharum*-dominated landscapes for species persistence (Akash et al., 2018; Dehar et al., 2024).

Black-breasted Parrotbill demonstrated a distinct habitat profile characterized by strong associations with *Phragmites* reed beds combined with active avoidance of wooded areas, as evidenced by the species' absolute requirement for proximity to *Phragmites* stands

($\beta = -0.455$, $z = -5.06$, $p < 0.001$) and significant positive relationship with distance to woodland ($\beta = 0.671$, $z = 3.49$, $p < 0.001$). This finding supports previous field observations documenting the species' restriction to reed-dominated grasslands and highlights the importance of maintaining open grassland configurations rather than allowing woody encroachment, which represents a significant threat to habitat quality (Allen, 2002; Bora & Saikia, 2024).

Marsh Babbler emerged as the most wetland-dependent of the three species, with *Phragmites* height representing the strongest positive predictor of species occurrence ($\beta = 0.503$, $z = 4.23$, $p < 0.001$) while distance to *Phragmites* showed the strongest negative association ($\beta = -2.108$, $z = -3.96$, $p < 0.001$), indicating the species' absolute dependence on *Phragmites* reed stands. The highly significant positive relationship with water occurrence ($\beta = 0.135$, $z = 2.74$, $p = 0.006$) reflects the species' fundamental association with wetland environments and supports its documented preference for marshy ground adjacent to swamps and rivers. This finding emphasizes the critical importance of maintaining hydrological connectivity and natural flooding regimes for sustaining viable Marsh Babbler populations, as disruption of these processes through dam construction or water diversion projects could have catastrophic impacts on species persistence (BirdLife International, 2024).

6.1.2 Anthropogenic pressures as critical limiting factors in species distribution

The threat assessment revealed that anthropogenic pressures represent critical limiting factors affecting all target species, with livestock grazing emerging as one of the most severe threats across the study region. Jerdon's Babbler exhibited the strongest negative response to grazing pressure ($\beta = -0.369$, $z = -5.13$, $p < 0.001$), indicating severe impacts on species occurrence patterns and supporting the species' documented preference for dense, undisturbed grassland stands. Fire regimes represented another major anthropogenic threat, with spatial analysis revealing problematic seasonal patterns where the pre-monsoon period (March-May) experienced the highest fire activity, affecting approximately 198,000 hectares and coinciding with the potential breeding season for all three target species. This temporal mismatch between fire occurrence and critical breeding

periods represents a significant conservation concern, as nest destruction and habitat degradation during breeding seasons can have disproportionate impacts on population viability (Beal-Neves et al., 2020; Doherty et al., 2024).

Agricultural expansion emerged as the most pervasive and persistent threat to grassland bird habitats throughout the study region, with extensive documentation of native grassland conversion to rice cultivation occurring across riverine islands and floodplain areas that serve as crucial species refugia. This finding aligns with global patterns affecting grassland birds, where agriculture represents the primary threat to grassland bird populations worldwide, with approximately 75% of studies identifying agricultural impacts as the leading cause of population declines (Douglas et al., 2023). The Brahmaputra floodplains exemplify this global pattern, with the conversion of native grasslands to rice cultivation eliminating habitat while simultaneously increasing edge effects and fragmentation that further degrade remaining habitat patches.

6.1.3 Climate change–induced reductions in suitable habitats for the three species

The climate change projections represent perhaps the most alarming findings of this research, revealing that all three species face catastrophic habitat contractions under projected climate scenarios, with vulnerability escalating dramatically under higher emission pathways and longer time horizons.

Jerdon's Babbler, despite having the most extensive current range spanning 265,460.48 km² across eight South and Southeast Asian countries, faces immediate habitat losses of 81-84% by 2021-2040 across all emission scenarios, escalating to near-complete extirpation with 99.94% habitat loss under SSP5-8.5 by century's end. These projected losses exceed those reported for other grassland bird species globally, highlighting the particular vulnerability of Asian grassland specialists to climate change impacts (Bateman et al., 2020; Mota et al., 2022).

Black-breasted Parrotbill projections demonstrate similarly devastating outcomes, with complete regional extirpation occurring by 2061-2080 under the high emission scenario despite the species' current habitat spanning 69,506.08 km² across northeastern Indian states. The species faces 70-99% habitat losses depending on emission pathway and time period, with Arunachal Pradesh emerging as the primary refugium under all scenarios.

Marsh Babbler shows substantial habitat contractions ranging from 71.50% under the conservative SSP1-2.6 scenario to 98.49% under SSP5-8.5 by century's end, with Assam and Arunachal Pradesh representing the sole potential refugia for long-term species persistence.

6.1.4 Identified potential climate refugia

The climate refugia analysis identified 6,161.935 km² of critical refuge habitat across northeastern India, representing areas projected to remain climatically suitable for one or more target species under future climate scenarios. The finding that 66.5% of refugia comprise two-species overlap zones and 10.5% represent three-species overlap areas provides strategic opportunities for synergistic conservation investments that maximize benefits across multiple threatened taxa simultaneously. This spatial congruence in climate requirements among target species suggests that landscape-scale conservation approaches may be more spatially and economically efficient than single-species strategies, supporting the development of multi-species conservation frameworks for grassland bird conservation in the region.

6.2 Conservation recommendations

6.2.1 Immediate habitat protection and management

6.2.1.1 Priority Protected Area Designation

Out of the total 6,161.935 km² of climate refugia identified, the 647.6 km² of three-species climate refugia demands immediate protected area designation, with priority focus on core refugia areas in Assam (551.4 km²) and Arunachal Pradesh (96.2 km²). These areas represent irreplaceable climate adaptation zones where all three species are projected to persist under future climate scenarios, making them critical targets for immediate conservation action. Protected area expansion should follow systematic conservation planning principles, ensuring adequate representation of habitat diversity within refugia boundaries while maintaining ecological connectivity between existing protected areas.

Current protected areas within the Brahmaputra floodplains, including Kaziranga National Park, Dibru-Saikhowa National Park, Manas National Park, and D'Ering Memorial Wildlife Sanctuary, should be evaluated for expansion to encompass identified

refugia areas. Buffer zones around core refugia should be established to minimize edge effects and provide additional habitat security under climate uncertainty. Climate adaptation management should include the establishment of buffer zones around core protected areas that can accommodate shifting habitat boundaries and the development of corridors that facilitate species movement as climate conditions change (Hannah et al., 2007).

6.2.1.2 *Grassland Habitat Restoration and Management*

Given the species-specific associations with particular grass types, *Saccharum* for Jerdon's Babbler, *Phragmites* for Black-breasted Parrotbill and Marsh Babbler, targeted habitat restoration programs should focus on re-establishing native grass communities in degraded areas. Restoration efforts should prioritize areas within identified refugia and connectivity corridors between existing populations.

Native seed collection and propagation programs should be established for key grass species, with particular emphasis on *Saccharum spontaneum*, *Phragmites karka*, and associated wetland vegetation. Restoration protocols should account for the dynamic hydrology of floodplain systems, ensuring that restored habitats can withstand seasonal flooding while providing appropriate vegetation structure for target species.

Invasive species control programs must be implemented to address threats from *Mikania micrantha*, *Ipomoea carnea*, and *Chromolaena odorata*, which alter vegetation structure and reduce habitat quality. Early detection and rapid response protocols should be developed for emerging invasive species threats. Invasive species management should focus on maintaining native plant communities that provide appropriate habitat structure and food resources for target species, utilizing both mechanical and chemical control methods where appropriate while minimizing impacts on native vegetation and wildlife (DiTomaso, 2000; Saalfeld et al., 2016).

6.2.1.3 *Fire Management and Prescribed Burning*

The documentation of peak fire activity during April, coinciding with potential breeding seasons, necessitates immediate implementation of fire management strategies that reduce wildfire risk while maintaining ecosystem integrity. Prescribed burning programs should be designed to create habitat heterogeneity at appropriate spatial scales while avoiding critical breeding periods.

Fire management plans should incorporate community-based approaches that engage local stakeholders in fire prevention and management activities. Traditional ecological knowledge regarding historical fire regimes should be integrated with scientific management approaches to develop culturally appropriate and ecologically effective strategies.

Firebreaks and fire suppression infrastructure should be strategically located to protect core habitat areas during peak fire season, while allowing controlled burns in designated areas to maintain grassland ecosystem health. Research on fire management in grassland systems has demonstrated that moderate disturbance regimes often support the highest grassland bird diversity, while either complete fire suppression or intensive burning reduces habitat suitability for many specialist species (Doherty et al., 2024; Robbins & Dale, 1999).

6.2.2 Threat mitigation strategies

6.2.2.1 Grazing Management and Livestock Regulation

The significant negative impacts of livestock grazing on all target species, particularly Jerdon's Babbler ($\beta = -0.369$, $z = -5.13$, $p < 0.001$), Grazing exclusion zones should be designated within core breeding habitats during critical reproductive periods (March-July). Alternative livelihood programs should be developed to reduce dependence on grassland grazing while maintaining community support for conservation efforts.

Monitoring protocols should be implemented to assess grazing impacts on vegetation structure and bird populations. The negative impacts of grazing and fire documented in this study emphasize the need for adaptive management protocols that can balance natural disturbance processes with species conservation requirements while accommodating traditional land uses by local communities (Fuhlendorf & Engle, 2004; Sharma et al., 2023).

6.2.2.2 Agricultural Land Use Planning

The pervasive threat of agricultural expansion requires integration of conservation planning with regional land use planning processes. Agricultural expansion should be directed away from identified refugia areas and critical habitat zones through zoning

regulations and incentive programs. Conservation easements and payment for ecosystem services programs should be established to compensate landowners for maintaining grassland habitats rather than converting to agriculture. These programs should prioritize areas within identified refugia and connectivity corridors. Sustainable agricultural practices should be promoted in buffer zones around critical habitats, including organic farming methods that reduce pesticide impacts on insect prey populations and integrated pest management approaches that minimize chemical inputs.

6.2.2.3 Water Resource Management and Hydrological Protection

The fundamental dependence of target species on specific hydrological regimes, particularly for Marsh Babbler which showed strong associations with water occurrence ($\beta = 0.135$, $z = 2.74$, $p = 0.006$), requires protection of natural flood cycles and wetland hydrology. Proposed dam construction and water diversion projects should be subject to comprehensive environmental impact assessment with particular attention to downstream grassland habitat impacts. Wetland restoration programs should focus on re-establishing natural hydrological connections between river channels and floodplain grasslands. Existing embankments and flood control structures should be evaluated for their impacts on natural flooding regimes, with selective removal or modification considered where appropriate.

Water quality protection measures should be implemented to address pollution from agricultural runoff and urban sources that may affect prey availability and habitat quality in wetland grasslands. The integration of environmental impact assessments that specifically consider grassland bird habitat requirements into water resource planning processes represents an essential step for ensuring that development projects do not compromise critical ecosystem functions (Pradhan et al., 2021a; van Oorschot et al., 2018).

6.2.2.4 Wind Energy Potential and Conservation Risks

Currently, there are no wind turbines installed in the Brahmaputra floodplain grasslands of Arunachal Pradesh and Assam, though the region experiences strong winds and has been identified in wind-mapping studies as having significant future wind energy potential, (National Institute of Wind Energy, 2023; Rahul & Prakash, 2018). This prospect

raises major conservation concerns, as these grasslands harbour critically endangered and endemic birds such as the Bengal florican and swamp grass babbler.

Studies show wind turbine mortality in flat grasslands can reach 1.24 ± 0.18 birds turbine⁻¹ month⁻¹, with annual landscape-level losses of ~4,464 birds per 1,000 km² (Roy et al., 2025). Long-term grassland wind farms in India recorded mean fatality rates of 0.26 animals per turbine, with displacement effects (Kumara et al., 2022). Flat terrain, habitat compression, monsoon-driven movements, reduced blade visibility, and species' naivety further increase collision vulnerability (Roy et al., 2025). With >50% declines already reported in India's grassland bird populations (India State of Forest Report, 2023), future wind development must adopt strict safeguards. Proven measures such as blade visibility enhancement (71.9% mortality reduction) and radar-based shutdown systems (May et al., 2020), combined with landscape-scale siting that integrates conservation corridors, will be critical to preventing population-level declines of these globally threatened species.

6.2.3 Climate adaptation strategies

6.2.3.1 Assisted Migration and Connectivity Enhancement

The severe habitat contractions projected under all climate scenarios necessitate consideration of assisted migration strategies for populations at risk of local extirpation. Translocation programs should be developed based on genetic assessments to ensure appropriate source populations and receiving sites. Habitat corridors should be established and maintained to facilitate natural range shifts in response to climate change. Corridor design should account for projected shifts in suitable climate space and incorporate stepping-stone habitats at appropriate intervals. Connectivity assessment should be conducted using landscape genetics approaches to identify barriers to dispersal and prioritize corridor establishment. Corridors should connect current populations with identified refugia areas and maintain linkages between different habitat types. Landscape-scale management should integrate conservation objectives with agricultural production, infrastructure development, and other land uses through comprehensive planning processes that consider cumulative impacts and management synergies across the landscape (Savary et al., 2024).

6.2.3.2 *Climate Monitoring and Early Warning Systems*

Comprehensive climate monitoring networks should be established within critical habitat areas to track local climate changes and their impacts on habitat suitability. Automated weather stations should be deployed to collect high-resolution temperature, precipitation, and humidity data.

Early warning systems should be developed to alert conservation managers to extreme weather events that may impact breeding success or survival. These systems should be integrated with habitat monitoring programs to assess climate impacts on vegetation phenology and prey availability. Adaptive management protocols should be established that allow rapid response to changing environmental conditions, including modification of management strategies based on observed climate impacts.

6.2.4 **Species-specific conservation suggestions**

6.2.4.1 *Jerdon's Babbler*

Given the species' overwhelming dependence on *Saccharum* grasslands and its extensive transboundary distribution, international coordination is essential for effective conservation. Regional conservation strategies also should be developed. *Saccharum* grassland protection should be prioritized across the species' range, with particular focus on maintaining large, contiguous stands that support viable breeding populations. Management protocols should address the species' preference for dense, undisturbed grasslands while allowing for natural disturbance regimes. Population monitoring programs should be established using standardized protocols across the species' range to track population trends and habitat quality. Genetic studies should be conducted to assess population connectivity and identify priorities for habitat corridor establishment.

6.2.4.2 *Black-breasted Parrotbill*

The species' restriction to northeastern India and extreme vulnerability to climate change necessitates immediate emergency conservation action. A species action plan should be developed with specific population targets and habitat protection goals. *Phragmites* reed bed restoration should be prioritized within Assam and Arunachal Pradesh, which emerges as the primary climate refugium. Management should focus on

maintaining optimal reed density and structure while ensuring appropriate water levels. Intensive population monitoring should be implemented using both traditional survey methods and new technologies such as acoustic monitoring to track population trends and breeding success. Research programs should focus on understanding the species' breeding ecology, habitat requirements, and response to management interventions.

6.2.4.3 *Marsh Babbler*

The species' dependence on wetland grasslands and strong avoidance of human settlements requires landscape-scale conservation planning that maintains large blocks of undisturbed wetland habitat. Priority should be given to protecting existing strongholds in Assam while restoring degraded wetlands in Arunachal Pradesh. Wetland restoration programs should focus on re-establishing appropriate vegetation structure and hydrological regimes. Management should address the species' requirement for dense *Phragmites* stands while maintaining habitat diversity at landscape scales. Water quality monitoring should be implemented to ensure that pollution does not impact prey availability or habitat suitability. Programs should address agricultural runoff, urban pollution, and other contamination sources.

6.3 Conclusion

This comprehensive study of three threatened grassland bird species in the Brahmaputra floodplains reveals the urgent need for immediate and coordinated conservation action to prevent extinctions and maintain ecosystem integrity under accelerating environmental change. The synthesis of habitat requirements, threat assessments, and climate projections provides a robust scientific foundation for evidence-based conservation planning that addresses both immediate pressures and long-term climate adaptation needs.

The finding that all three species face catastrophic habitat losses under projected climate scenarios, ranging from 81% to 99.94% by century's end, represents one of the most severe climate vulnerabilities documented among Asian grassland birds. These projections, combined with ongoing anthropogenic pressures including livestock grazing, fire disturbance, and agricultural expansion, indicate that business-as-usual approaches will likely result in regional extinctions within the next few decades.

However, the identification of 6,161.935 km² of critical climate refugia, particularly the 647.6 km² of three-species overlap zones, provides strategic opportunities for conservation investments that can benefit multiple threatened species simultaneously. The concentration of refugia areas in Assam (77.0% of total refuge area) and Arunachal Pradesh (23.0%) offers clear geographic priorities for immediate protected area expansion and habitat management interventions.

The species-specific habitat requirements documented through this research, Jerdon's Babbler's dependence on *Saccharum* grasslands, Black-breasted Parrotbill's association with *Phragmites* reed beds, and Marsh Babbler's requirement for wetland grasslands, provide precise targets for habitat restoration and management efforts. These findings enable development of targeted conservation strategies that address the specific ecological needs of each species while recognizing opportunities for synergistic management approaches.

The conservation recommendations developed in this synthesis call for urgent, multi-scale action, including the designation of protected areas for identified refugia, implementation of fire and grazing management, habitat restoration with key grass species, and development of climate adaptation strategies such as assisted migration and ex-situ conservation. The proposed adaptive management framework emphasizes flexible, responsive strategies supported by comprehensive monitoring, regular reviews, and integration of emerging science to address the unprecedented challenges of climate change. Successful implementation will require stronger institutional capacity, improved inter-agency coordination, and meaningful community participation, while the policy integration pathways outlined here provide mechanisms for embedding conservation objectives into land use planning, agricultural development, and climate adaptation policies.

Perhaps most importantly, this research demonstrates the critical importance of rapid action in addressing the grassland bird conservation crisis. The narrow window of opportunity for preventing extinctions demands immediate implementation of conservation measures while longer-term strategies are developed and implemented. Delays in conservation action will likely result in irreversible losses that cannot be compensated by future efforts.

The Brahmaputra floodplains represent one of the world's most important grassland ecosystems, supporting globally significant biodiversity and providing essential ecosystem services to millions of people. The conservation strategies developed through this research provide a roadmap for protecting this unique ecosystem and its threatened bird communities, but success depends on immediate and sustained commitment from governments, conservation organizations, researchers, and local communities.

The broader implications of this research extend beyond the three focal species to encompass the conservation of South Asian grassland ecosystems generally. The methodological approaches developed here can be applied to other threatened grassland species and ecosystems, while the conservation strategies provide models for addressing similar challenges elsewhere in the region.

Ultimately, the success of grassland bird conservation in the Brahmaputra floodplains will depend on our collective ability to implement comprehensive, science-based conservation strategies that address both immediate threats and long-term climate challenges. The evidence presented in this thesis provides the scientific foundation for such strategies, but their implementation requires unprecedented cooperation and commitment from all stakeholders involved in the conservation of these globally important ecosystems.

The three threatened grassland bird species studied indicated broader ecosystem health and could potentially serve as ambassadors for grassland conservation. Their conservation not only can make an important contribution to global biodiversity protection but can also be a critical test of our capacity to implement effective conservation strategies under accelerating environmental changes.

References

REFERENCES

- Agarwal, S. K., Nakkella, A. K., & Rout, S. (2021). *Herbal Medicine–A Benign and Conventional Medical System*. https://www.academia.edu/download/66275235/immortal_publication.pdf
- Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B., & Anderson, R. P. (2015). spThin: An R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography*, 38(5), 541–545. <https://doi.org/10.1111/ecog.01132>
- Akash, M., Khan, T., & Chowdhury, S. U. (2018). Association of grassland birds with Saccharum-Imperata patch in a northeastern tea estate of Bangladesh. *Journal of Threatened Taxa*, 10(7), 11831–11843.
- Alam, M. M., Hossain, M. S., & Akter, K. (2024). Assessment of Long-Term Trends in Pre-Monsoon Rainfall and Temperature for Various Districts Using Moving Average and Exponential Moving Average Methods: <https://doi.org/10.46610/JoEES.2024.v09i03.004>. *Journal of Environmental Engineering and Studies*, 30–64.
- Allen, D. (2002). A bird survey of the Amarpur area of the Dibru-Saikhowa Biosphere Reserve, Assam, India. *Forktail*, 87–92.
- Andrews, M. B., Ridley, J. K., Wood, R. A., Andrews, T., Blockley, E. W., Booth, B., Burke, E., Dittus, A. J., Florek, P., Gray, L. J., Haddad, S., Hardiman, S. C., Hermanson, L., Hodson, D., Hogan, E., Jones, G. S., Knight, J. R., Kuhlbrodt, T., Misios, S., ... Sutton, R. T. (2020). Historical Simulations With HadGEM3-GC3.1 for CMIP6. *Journal of Advances in Modeling Earth Systems*, 12(6), e2019MS001995. <https://doi.org/10.1029/2019MS001995>
- Ao, Y., Li, H., Zhu, L., Ali, S., & Yang, Z. (2019). The linear random forest algorithm and its advantages in machine learning assisted logging regression modeling. *Journal of Petroleum Science and Engineering*, 174, 776–789.
- Araújo, M. B., & New, M. (2007). Ensemble forecasting of species distributions. *Trends in Ecology & Evolution*, 22(1), 42–47.

- Areendran, G., Puri, K., Raj, K., Mazumdar, S., & Joshi, R. (2018). A geospatial study to assess the land use land cover of Mehao Wildlife Sanctuary in Arunachal Pradesh, India. *Asian Journal of Geographical Research*, 1(2), 1–8.
- Arsirii, O. O., Krachunov, H. A., Smyk, S. Y., & Troianovska, Y. L. (2022). Methods of analysis and visualization of active fires and burnt areas of geospatial data. *Вісник Сучасних Інформаційних Технологій*, 5(1), 62–73.
- Baker, E. C. (1932). The nidification of birds of the Indian Empire. (*No Title*). <https://cir.nii.ac.jp/crid/1130000798141869952>
- Baker, E. S. (1922). *The fauna of British India, including Ceylon and Burma: Birds*. Today and Tomorrow Publisher.
- Bakker, K. K., Naugle, D. E., & Higgins, K. F. (2002). Incorporating Landscape Attributes into Models for Migratory Grassland Bird Conservation. *Conservation Biology*, 16(6), 1638–1646. <https://doi.org/10.1046/j.1523-1739.2002.01328.x>
- Barman, D., Kumar, A., Ahmed, M. F., & Devi, A. (2024). Record of threatened Mishmi Takin (*Budorcas taxicolor taxicolor* Hodgson, 1850) from Lower Dibang Valley District, Arunachal Pradesh, India. *Records of the Zoological Survey of India*, 85–91.
- Barrero, A., Gómez-Catasús, J., Pérez-Granados, C., Bustillo-de La Rosa, D., & Traba, J. (2024). Conspecific density and habitat quality drive the defence and vocal behaviour of a territorial passerine. *Ibis*, 166(3), 826–843. <https://doi.org/10.1111/ibi.13295>
- Basumatary, S. (2023). *Floristic Diversity of Chirang Reserve Forest of Bodoland Territorial Region in Assam With Special Reference to Threatened and Endemic Plants* [PhD Thesis, DEPT: BOTANY]. http://14.139.213.3:8080/jspui/bitstream/123456789/326/3/03_Contents.pdf
- Bateman, B. L., Wilsey, C., Taylor, L., Wu, J., LeBaron, G. S., & Langham, G. (2020). North American birds require mitigation and adaptation to reduce vulnerability to climate change. *Conservation Science and Practice*, 2(8), e242. <https://doi.org/10.1111/csp2.242>

- Bayne, E. M., Habib, L., & Boutin, S. (2008). Impacts of Chronic Anthropogenic Noise from Energy-Sector Activity on Abundance of Songbirds in the Boreal Forest. *Conservation Biology*, 22(5), 1186–1193. <https://doi.org/10.1111/j.1523-1739.2008.00973.x>
- Beal-Neves, M., Chiarani, E., Ferreira, P. M. A., & Fontana, C. S. (2020). The role of fire disturbance on habitat structure and bird communities in South Brazilian Highland Grasslands. *Scientific Reports*, 10(1), 19708.
- Bede-Fazekas, Á., & Somodi, I. (2020). The way bioclimatic variables are calculated has impact on potential distribution models. *Methods in Ecology and Evolution*, 11(12), 1559–1570. <https://doi.org/10.1111/2041-210X.13488>
- Bernardino, J., Bevanger, K., Barrientos, R., Dwyer, J. F., Marques, A. T., Martins, R. C., Shaw, J. M., Silva, J. P., & Moreira, F. (2018). Bird collisions with power lines: State of the art and priority areas for research. *Biological Conservation*, 222, 1–13.
- Bharadwaj, A., Mhamane, S., Bangal, P., Menon, T., Isvaran, K., & Quader, S. (2024). Assessment of long-term trends in a threatened grassland bird community using daily bird lists. *Bird Conservation International*, 34, e3.
- Bhatnagar, Y. V., Mathur, V. B., Sathyakumar, S., Pal, R., Ghoshal, A., Sharma, R. K., Bijoor, A., Raghunath, R., Timbadia, R., & Lal, P. (2024). Securing India's snow leopards: Status, threats, and conservation. In *Snow Leopards* (pp. 513–529). Elsevier. <https://www.sciencedirect.com/science/article/pii/B9780323857758000030>
- Bhattachaiyya, N. N., & Bora, A. K. (1997). Floods of the Brahmaputra River in India. *Water International*, 22(4), 222–229. <https://doi.org/10.1080/02508069708686709>
- Bhattacharyya, D., & Bora, A. (2018). *Angiosperm Diversity in Barail Wildlife Sanctuary, Assam With a Note on Rare, Endangered & Threatened (Ret) Taxa*.
- Bhuyan, M. J., & Deka, N. (2024). Beyond natural flow: Human-directed course change of the Kolong river in Nagaon, Assam, (India) and its socio-ecological implications. *River*, 3(4), 408–415. <https://doi.org/10.1002/rvr2.112>
- BirdLife, I. (2018). *State of the world's birds: Taking the pulse of the planet*.

- BirdLife International. (2021). *Jerdon's Babbler Chrysomma Altirostre Species* [Species factsheet: Jerdon's Babbler Chrysomma altirostre.]. Datazone.Birdlife.Org. <https://datazone.birdlife.org/species/factsheet/jerdons-babbler-chrysomma-altirostre> on 12/03/2025
- BirdLife International. (2024a). *Black-breasted Parrotbill Paradoxornis Flavirostris Species*. BirdLife DataZone. <https://datazone.birdlife.org/species/factsheet/black-breasted-parrotbill-paradoxornis-flavirostris>
- BirdLife International. (2024b). *Marsh Babbler Pellorneum Palustre Species*. BirdLife DataZone. <https://datazone.birdlife.org/species/factsheet/marsh-babbler-pellorneum-palustre>
- BirdLife International. (2024c). *Species factsheet: Marsh Babbler Pellorneum palustre*. Downloaded from <https://datazone.birdlife.org/species/factsheet/marsh-babbler-pellorneum-palustre>. BirdLife DataZone. <https://datazone.birdlife.org/species/factsheet/marsh-babbler-pellorneum-palustre>
- BirdLife International. (2025). *BirdLife DataZone*. <https://datazone.birdlife.org/site/factsheet/kaziranga-national-park>
- Blackburn, T. M., Cassey, P., Duncan, R. P., Evans, K. L., & Gaston, K. J. (2004). Avian Extinction and Mammalian Introductions on Oceanic Islands. *Science*, 305(5692), 1955–1958. <https://doi.org/10.1126/science.1101617>
- Bora, C., & Saikia, P. K. (2024). MaxEnt modelling for predicting habitat suitability and future range of Black-breasted Parrotbill (*Paradoxornis flavirostris* Gould, 1836) in Northeast India. *Ornis Hungarica*, 32(1), 31–44. <https://doi.org/10.2478/orhu-2024-0003>
- Borah, D., Tangjang, S., Das, A. P., Kafley, P., & Khapugin, A. A. (2020). Native vascular flora of Behali Reserve Forest (Assam, India) with global Iucn Red List assessment of two endemic species. *Contributii Botanice*, 55.
- Both, C. (2010). Food availability, mistiming, and climatic change. *Effects of Climate Change on Birds*, 129–147.

- Brahmaputra and Barak Basin. (2007). In S. K. Jain, P. K. Agarwal, & V. P. Singh, *Hydrology and Water Resources of India* (Vol. 57, pp. 419–472). Springer Netherlands. https://doi.org/10.1007/1-4020-5180-8_9
- Brennan, L. A., & Kuvlesky, W. P. (2005). Invited Paper: North American Grassland Birds: An Unfolding Conservation Crisis? *Journal of Wildlife Management*, 69(1), 1–13. [https://doi.org/10.2193/0022-541X\(2005\)069%253C0001:NAGBAU%253E2.0.CO;2](https://doi.org/10.2193/0022-541X(2005)069%253C0001:NAGBAU%253E2.0.CO;2)
- Brooks, M. L., D’antonio, C. M., Richardson, D. M., Grace, J. B., Keeley, J. E., DiTomaso, J. M., Hobbs, R. J., Pellant, M., & Pyke, D. (2004). Effects of invasive alien plants on fire regimes. *BioScience*, 54(7), 677–688.
- Buchhorn, M., Lesiv, M., Tsendbazar, N.-E., Herold, M., Bertels, L., & Smets, B. (2020). Copernicus global land cover layers—Collection 2. *Remote Sensing*, 12(6), 1044.
- Buxton, V. L., & Benson, T. J. (2016). Conservation-priority grassland bird response to urban landcover and habitat fragmentation. *Urban Ecosystems*, 19(2), 599–613. <https://doi.org/10.1007/s11252-016-0527-3>
- Byers, O., Copsey, J., Lees, C., Miller, P., & Traylor-Holzer, K. (2022). Reversing the decline in threatened species through effective conservation planning. *Diversity*, 14(9), 754.
- Cavalcanti, I. F. A., Souza, D. C., Kubota, P. Y., Coelho, C. A. S., Figueroa, S. N., & Baker, J. C. A. (2022). The global monsoon system representation in BAM -v1.2 and HADGEM3 climate simulations. *International Journal of Climatology*, 42(15), 8089–8111. <https://doi.org/10.1002/joc.7694>
- Chai, R. (2014). Morphometric analysis of Digaru river basin, Lohit District, Arunachal Pradesh. *IOSR J Environ Sci Toxicol Food Technol*, 8(10), 30–49.
- Chakdar, B., Singha, H., & Choudhury, M. R. (2019). Bird community of Rajiv Gandhi Orang National Park, Assam. *Journal of Asia-Pacific Biodiversity*, 12(4), 498–507.
- Chakraborty, D., Roy, A., Singh, N. U., Saha, S., Das, S. K., Mridha, N., Yumnam, A., Paul, P., Gowda, C., & Biam, K. P. (2025). Assessing Climate Change Impact on Rainfall Patterns in Northeastern India and Its Consequences on Water Resources and Rainfed Agriculture. *Earth*, 6(1), 2.

- Champion, H. G., & Seth, S. K. (1968). *A revised survey of the forest types of India*. Manager of publications.
- Choudhury, A. (2011). Records of Black-breasted Parrotbill *Paradoxornis flavirostris* from Manas National Park, Assam, in north-east India. In *FORKTAIL* (Issue 27, pp. 111–112). ORIENTAL BIRD CLUB PO BOX 324, BEDFORD, MK42 0WG, ENGLAND.
- Cohen, W. B., Healey, S. P., Yang, Z., Zhu, Z., & Gorelick, N. (2020). Diversity of algorithm and spectral band inputs improves Landsat monitoring of forest disturbance. *Remote Sensing*, 12(10), 1673.
- Crispim, T., Valerio, F., Marques, A. T., Pita, R., Godinho, S., & Silva, J. P. (2024). *High-resolution species distribution modelling reveals spatio-temporal variability of habitat suitability in a declining grassland bird*. <https://dspace.uevora.pt/rdpc/handle/10174/38567>
- Cruz-Cárdenas, G., López-Mata, L., Villaseñor, J. L., & Ortiz, E. (2014). Potential species distribution modeling and the use of principal component analysis as predictor variables. *Revista Mexicana de Biodiversidad*, 85(1), 189–199.
- Daham, A., Smith, G. H. S., Nicholas, A. P., Gasparotto, A., Clark, J., & Yasmin, T. (2024). Sand mining across the Ganges–Brahmaputra–Meghna Catchment; assessment of activity and implications for sediment delivery. *Environmental Research Letters*, 19(8), 084030.
- Dantas-Queiroz, M. V., Cacossi, T. D. C., Leal, B. S. S., Chaves, C. J. N., Vasconcelos, T. N. C., Versieux, L. D. M., & Palma-Silva, C. (2021). Underlying microevolutionary processes parallel macroevolutionary patterns in ancient neotropical mountains. *Journal of Biogeography*, 48(9), 2312–2327. <https://doi.org/10.1111/jbi.14154>
- Das, A., Ghosh, P. K., Choudhury, B. U., Patel, D. P., Munda, G. C., Ngachan, S. V., & Chowdhury, P. (2009). Climate change in North East India: Recent facts and events–worry for agricultural management. *Proceedings of the Workshop on Impact of Climate Change on Agriculture*, 2009(December), 32–37. <https://www.academia.edu/download/83084327/2-114.pdf>

- Daskalova, G. N., Myers-Smith, I. H., Bjorkman, A. D., Blowes, S. A., Supp, S. R., Magurran, A. E., & Dornelas, M. (2020). Landscape-scale forest loss as a catalyst of population and biodiversity change. *Science*, 368(6497), 1341–1347. <https://doi.org/10.1126/science.aba1289>
- Dehar, P. S., Tripathi, K., Rout, S., & Kumar, S. (2024). Kans Grass (*Saccharum spontaneum* L.) and associated small birds: A conservation aspect. *Sharma BP, Das K, Saradar B and Dehar PS. Animal-Plant Interaction*, 4.
- Demir, S., & Sahin, E. K. (2023). An investigation of feature selection methods for soil liquefaction prediction based on tree-based ensemble algorithms using AdaBoost, gradient boosting, and XGBoost. *Neural Computing and Applications*, 35(4), 3173–3190. <https://doi.org/10.1007/s00521-022-07856-4>
- Dennis, P., Young, M. R., & Gordon, I. J. (1998). Distribution and abundance of small insects and arachnids in relation to structural heterogeneity of grazed, indigenous grasslands. *Ecological Entomology*, 23(3), 253–264. <https://doi.org/10.1046/j.1365-2311.1998.00135.x>
- Deomurari, A., Sharma, A., Ghose, D., & Singh, R. (2023). Projected shifts in bird distribution in India under climate change. *Diversity*, 15(3), 404.
- Derner, J. D., Lauenroth, W. K., Stapp, P., & Augustine, D. J. (2009). Livestock as ecosystem engineers for grassland bird habitat in the western Great Plains of North America. *Rangeland Ecology & Management*, 62(2), 111–118.
- Devi, A., Hussain, S. A., Sharma, M., Gopi, G. V., & Badola, R. (2022). Seasonal pattern of food habits of large herbivores in riverine alluvial grasslands of Brahmaputra floodplains, Assam. *Scientific Reports*, 12(1), 482.
- Didham, R. K., Tylianakis, J. M., Gemmell, N. J., Rand, T. A., & Ewers, R. M. (2007). Interactive effects of habitat modification and species invasion on native species decline. *Trends in Ecology & Evolution*, 22(9), 489–496.
- DiTomaso, J. M. (2000). Invasive weeds in rangelands: Species, impacts, and management. *Weed Science*, 48(2), 255–265.

- Doherty, T. S., Dickman, C. R., Nimmo, D. G., & Ritchie, E. G. (2015). Multiple threats, or multiplying the threats? Interactions between invasive predators and other ecological disturbances. *Biological Conservation*, 190, 60–68.
- Doherty, T. S., Macdonald, K. J., Nimmo, D. G., Santos, J. L., & Geary, W. L. (2024). Shifting fire regimes cause continent-wide transformation of threatened species habitat. *Proceedings of the National Academy of Sciences*, 121(18). <https://doi.org/10.1073/pnas.2316417121>
- Donald, P. F., Green, R. E., & Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 268(1462), 25–29. <https://doi.org/10.1098/rspb.2000.1325>
- Douglas, D. J. T., Waldinger, J., Buckmire, Z., Gibb, K., Medina, J. P., Sutcliffe, L., Beckmann, C., Collar, N. J., Jansen, R., Kamp, J., Little, I., Sheldon, R., Yanosky, A., & Koper, N. (2023). A global review identifies agriculture as the main threat to declining grassland birds. *Ibis*, 165(4), 1107–1128. <https://doi.org/10.1111/ibi.13223>
- Drema, L., Gautam, S., & Rawat, S. (2024). Climatic trends and its impact on reference evapotranspiration and crop water requirement of rice crop in Arunachal Pradesh, India. *Journal of Agrometeorology*, 26(2), 220–224.
- Drew, J. A., & Henne, A. P. (2006). Conservation biology and traditional ecological knowledge: Integrating academic disciplines for better conservation practice. *Ecology and Society*, 11(2). <https://www.jstor.org/stable/26266033>
- Dudgeon, D. (2000). Large-scale hydrological changes in tropical Asia: Prospects for riverine biodiversity: the construction of large dams will have an impact on the biodiversity of tropical Asian rivers and their associated wetlands. *BioScience*, 50(9), 793–806.
- Durán, A. P., Green, J. M. H., West, C. D., Visconti, P., Burgess, N. D., Virah-Sawmy, M., & Balmford, A. (2020). A practical approach to measuring the biodiversity impacts of land conversion. *Methods in Ecology and Evolution*, 11(8), 910–921. <https://doi.org/10.1111/2041-210X.13427>

- Dutta, B., & Sarma, J. K. (2023). Ichthyofaunal diversity of Brahmaputra river and its adjoining tributaries: A review. *Intern J Zool Investig*, 9(1), 1008–1020.
- Escuin, S., Navarro, R., & Fernández, P. (2008). Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. *International Journal of Remote Sensing*, 29(4), 1053–1073. <https://doi.org/10.1080/01431160701281072>
- Evans, J. S., Murphy, M. A., Holden, Z. A., & Cushman, S. A. (2011). Modeling Species Distribution and Change Using Random Forest. In C. A. Drew, Y. F. Wiersma, & F. Huettmann (Eds.), *Predictive Species and Habitat Modeling in Landscape Ecology* (pp. 139–159). Springer New York. https://doi.org/10.1007/978-1-4419-7390-0_8
- Fairbairn, S. E., & Dinsmore, J. J. (2001). Local and landscape-level influences on wetland bird communities of the prairie pothole region of Iowa, USA. *Wetlands*, 21(1), 41–47. [https://doi.org/10.1672/0277-5212\(2001\)021%255B0041:LALLIO%255D2.0.CO;2](https://doi.org/10.1672/0277-5212(2001)021%255B0041:LALLIO%255D2.0.CO;2)
- Flannigan, M., Cantin, A. S., De Groot, W. J., Wotton, M., Newbery, A., & Gowman, L. M. (2013). Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, 294, 54–61.
- Fletcher Jr, R. J., & Koford, R. R. (2002). Habitat and landscape associations of breeding birds in native and restored grasslands. *The Journal of Wildlife Management*, 1011–1022.
- Fletcher, R. J., & Koford, R. R. (2003). Changes in breeding bird populations with habitat restoration in northern Iowa. *The American Midland Naturalist*, 150(1), 83–94.
- Forcina, G., Panayides, P., Guerrini, M., Nardi, F., Gupta, B. K., Mori, E., Al-Sheikhly, O. F., Mansoori, J., Khaliq, I., & Rank, D. N. (2012). Molecular evolution of the Asian francolins (*Francolinus*, Galliformes): A modern reappraisal of a classic study in speciation. *Molecular Phylogenetics and Evolution*, 65(2), 523–534.
- Friberg, N., Harrison, L., O'Hare, M., & Tullos, D. (2017). *Restoring rivers and floodplains: Hydrology and sediments as drivers of Change*, *Ecohydrology*, 10, e1884.

- Fuhlendorf, S. D., & Engle, D. M. (2004). Application of the fire–grazing interaction to restore a shifting mosaic on tallgrass prairie. *Journal of Applied Ecology*, 41(4), 604–614. <https://doi.org/10.1111/j.0021-8901.2004.00937.x>
- Fuhlendorf, S. D., Harrell, W. C., Engle, D. M., Hamilton, R. G., Davis, C. A., & Leslie, D. M. (2006). Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. *Ecological Applications*, 16(5), 1706–1716. [https://doi.org/10.1890/1051-0761\(2006\)016%255B1706:SHBTBF%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016%255B1706:SHBTBF%255D2.0.CO;2)
- Game, E. T., Kareiva, P., & Possingham, H. P. (2013). Six Common Mistakes in Conservation Priority Setting. *Conservation Biology*, 27(3), 480–485. <https://doi.org/10.1111/cobi.12051>
- Georganos, S., Grippa, T., Niang Gadiaga, A., Linard, C., Lennert, M., Vanhuysse, S., Mboga, N., Wolff, E., & Kalogirou, S. (2021). Geographical random forests: A spatial extension of the random forest algorithm to address spatial heterogeneity in remote sensing and population modelling. *Geocarto International*, 36(2), 121–136. <https://doi.org/10.1080/10106049.2019.1595177>
- Getis, A., & Ord, J. K. (1992). The Analysis of Spatial Association by Use of Distance Statistics. *Geographical Analysis*, 24(3), 189–206. <https://doi.org/10.1111/j.1538-4632.1992.tb00261.x>
- Ghosh, T., Kakati, P., Sharma, A., & Mondol, S. (2024). Optimising future rhino population management strategies using insights from genetic health assessments across India. *bioRxiv*, 2024–08.
- Ghosh-Harihar, M., An, R., Athreya, R., Borthakur, U., Chanchani, P., Chetry, D., Datta, A., Harihar, A., Karanth, K. K., & Mariyam, D. (2019). Protected areas and biodiversity conservation in India. *Biological Conservation*, 237, 114–124.
- Gibson, D. J., Seastedt, T. R., & Briggs, J. M. (1993). Management Practices in Tallgrass Prairie: Large- and Small-Scale Experimental Effects on Species Composition. In F. B. Samson & F. L. Knopf, *Ecosystem Management* (pp. 106–115). Springer New York. https://doi.org/10.1007/978-1-4612-4018-1_12

- Gogoi, D., & Gogoi, B. (2022). Endangering the Endangered: The Poaching and Conservation Conundrum Facing the Greater Indian One-Horned Rhinoceros in Kaziranga National Park, Assam, India. *Journal of International Wildlife Law & Policy*, 25(2), 159–175. <https://doi.org/10.1080/13880292.2022.2124609>
- Goswami, P., & Singha, S. (2023). Fish diversity of the Beki River, Assam, India: Present status and conservation needs. *Ecocycles*, 9(2), 1–6.
- Goswami, U., Sarma, J. N., & Patgiri, A. D. (1999). River channel changes of the Subansiri in Assam, India. *Geomorphology*, 30(3), 227–244.
- Gould, J. (1836). Characters of some new Birds in the Society's Collection, including two new genera, Paradoxornis and Actinodura. *Proceedings of the Zoological Society of London*, 4, 17–19.
- Gould, J. (1872). Plate 65. Pellorneum palustre. In *The Birds of Asia*. Taylor and Francis, London, 3.
- Grassland Birds. (2025). *State of the Birds 2025*. <https://www.stateofthebirds.org/2025/grassland-birds/>
- Griffis, E. K., & Campa III, H. (2023). Upland Sandpiper (*Bartramia longicauda*) breeding habitat ecology, home range, and nest site conservation guidelines. *The Wilson Journal of Ornithology*, 135(4), 502–511.
- Grimmett, R., Inskipp, C., & Inskipp, T. (2016). *Birds of the Indian Subcontinent*. (2nd ed.). Oxford University Press, Oxford.
- Grimmett, R., Inskipp, C., Inskipp, T., & Baral, H. S. (2016). *Field Guide to the Birds of Nepal*. Bloomsbury Publishing.
- Guisan, A., Tingley, R., Baumgartner, J. B., Naujokaitis-Lewis, I., Sutcliffe, P. R., Tulloch, A. I. T., Regan, T. J., Brotons, L., McDonald-Madden, E., Mantyka-Pringle, C., Martin, T. G., Rhodes, J. R., Maggini, R., Setterfield, S. A., Elith, J., Schwartz, M. W., Wintle, B. A., Broennimann, O., Austin, M., ... Buckley, Y. M. (2013). Predicting species distributions for conservation decisions. *Ecology Letters*, 16(12), 1424–1435. <https://doi.org/10.1111/ele.12189>

- Hairston, N. G., Smith, F. E., & Slobodkin, L. B. (1960). Community Structure, Population Control, and Competition. *The American Naturalist*, 94(879), 421–425. <https://doi.org/10.1086/282146>
- Hannah, L., Midgley, G., Andelman, S., Araújo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., & Williams, P. (2007). Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, 5(3), 131–138. [https://doi.org/10.1890/1540-9295\(2007\)5%255B131:PANIAC%255D2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5%255B131:PANIAC%255D2.0.CO;2)
- Hao, T., Elith, J., Guillera-Arroita, G., & Lahoz-Monfort, J. J. (2019). A review of evidence about use and performance of species distribution modelling ensembles like BIOMOD. *Diversity and Distributions*, 25(5), 839–852. <https://doi.org/10.1111/ddi.12892>
- Hao, T., Elith, J., Lahoz-Monfort, J. J., & Guillera-Arroita, G. (2020). Testing whether ensemble modelling is advantageous for maximising predictive performance of species distribution models. *Ecography*, 43(4), 549–558. <https://doi.org/10.1111/ecog.04890>
- Harif Parengal, Padijareveedu Ramachandran Arun, Sarbasis Dutta, & Anisha Joy. (2025). Distribution, habitat shift, and conservation needs of Jerdon’s Babbler (*Chrysomma altirostre*): A study of a vulnerable grassland specialist. *Ornis Hungarica*, 33(2).
- Hegde, S. N. (2020). Status of Orchid Diversity, Conservation, and Research and Development in Arunachal Pradesh: An Overview. In S. M. Khasim, S. N. Hegde, M. T. González-Arno, & K. Thammasiri (Eds.), *Orchid Biology: Recent Trends & Challenges* (pp. 223–235). Springer Singapore. https://doi.org/10.1007/978-981-32-9456-1_12
- Hein, T., Schwarz, U., Habersack, H., Nichersu, I., Preiner, S., Willby, N., & Weigelhofer, G. (2016). Current status and restoration options for floodplains along the Danube River. *Science of the Total Environment*, 543, 778–790.
- Henwood, W. D. (2010). Toward a strategy for the conservation and protection of the world’s temperate grasslands. *Great Plains Research*, 121–134.

- Herkert, J. R. (1994). The Effects of Habitat Fragmentation on Midwestern Grassland Bird Communities. *Ecological Applications*, 4(3), 461–471. <https://doi.org/10.2307/1941950>
- Herse, M. R., With, K. A., & Boyle, W. A. (2020). Grassland fragmentation affects declining tallgrass prairie birds most where large amounts of grassland remain. *Landscape Ecology*, 35(12), 2791–2804. <https://doi.org/10.1007/s10980-020-01064-y>
- Hilton, G. M., & Cuthbert, R. J. (2010). Review article: The catastrophic impact of invasive mammalian predators on birds of the UK Overseas Territories: a review and synthesis. *Ibis*, 152(3), 443–458. <https://doi.org/10.1111/j.1474-919X.2010.01031.x>
- Hossain, S., Cloke, H. L., Ficchi, A., Turner, A. G., & Stephens, E. M. (2021). Hydrometeorological drivers of flood characteristics in the Brahmaputra river basin in Bangladesh. *Hydrology and Earth System Sciences Discussions*, 2021, 1–28.
- Huang, D., An, Q., Huang, S., Tan, G., Quan, H., Chen, Y., Zhou, J., & Liao, H. (2023). Biomod2 modeling for predicting the potential ecological distribution of three *Fritillaria* species under climate change. *Scientific Reports*, 13(1), 18801.
- India State of Forest Report. (2023). *India State of Forest Report*. <https://www.pib.gov.in/www.pib.gov.in/Pressreleaseshare.aspx?PRID=2086742>
- Islam, N., Ahmed, A., Barman, R., Deka, S., Choudhury, B., Saikia, P. K., & Deka, J. (2022). Revival of Eastern Swamp Deer *Rucervus duvaucelii ranjitsinhi* (Groves, 1982) in Manas National Park of Assam, India. *Journal of Threatened Taxa*, 14(1), 20488–20493.
- Jahan, I., Savini, T., Thompson, P. M., Round, P. D., & Gale, G. A. (2022a). Microhabitat variables influencing the presence and abundance of birds in floodplain grassland of the lower Ganges and Brahmaputra rivers, Bangladesh. *Global Ecology and Conservation*, 38, e02201.
- Jahan, I., Savini, T., Thompson, P. M., Round, P. D., & Gale, G. A. (2022b). Microhabitat variables influencing the presence and abundance of birds in floodplain grassland of the lower Ganges and Brahmaputra rivers, Bangladesh. *Global Ecology and Conservation*, 38, e02201.

- Jerdon, T. C. (1862). Notice of some New Species of Birds from Upper Burmah. *Ibis*, 4(1), 19–23. <https://doi.org/10.1111/j.1474-919X.1862.tb07470.x>
- Johnson, R. G., & Temple, S. A. (1990). Nest predation and brood parasitism of tallgrass prairie birds. *The Journal of Wildlife Management*, 106–111.
- Joshi, B. D., Dalui, S., Singh, S. K., Mukherjee, T., Chandra, K., Sharma, L. K., & Thakur, M. (2021). Siang river in Arunachal Pradesh splits red panda into two phylogenetic species. *Mammalian Biology*, 101(1), 121–124. <https://doi.org/10.1007/s42991-020-00094-y>
- Kamal, M. M., Sanjid, T. I., Piya, F., & Rony, A. (2024). The August 2024 Bangladesh Flood: Examining Meteorological Triggers, Forecasting Limitations, and Cross-Border Water Dynamics. *AGU Fall Meeting Abstracts*, 2024, NH22B-03. <https://ui.adsabs.harvard.edu/abs/2024AGUFMNH22B..03K/abstract>
- Kamp, J., Koshkin, M. A., Bragina, T. M., Katzner, T. E., Milner-Gulland, E. J., Schreiber, D., Sheldon, R., Shmalenko, A., Smelansky, I., Terraube, J., & Urazaliev, R. (2016). Persistent and novel threats to the biodiversity of Kazakhstan’s steppes and semi-deserts. *Biodiversity and Conservation*, 25(12), 2521–2541. <https://doi.org/10.1007/s10531-016-1083-0>
- Kanwal, K., & Lodhi, M. (2018). *Climate Change Impact on Plant Biodiversity of Arunachal Himalaya: A Review*. 33, 15–26.
- Keating, M. P., Williams, P. J., Robb, J. R., Buderman, F. E., Lewis, J. P., Vanosdol, T., & Harer, R. (2023). Henslow’s Sparrow shows positive response to prescribed fire rotation. *Ornithological Applications*, 125(3), duad018.
- Khan, A. A., Hussain, T., Rafay, M., Shahzad, M. I., & Ruby, T. (2014). Novel microsatellite based population genetic analysis of Pakistan endemic, jerdon’s babbler (*chrysomma altirostre*: Aves) from indus plains. *International Journal of Biosciences (IJB)*, 5(1), 97–103.
- Khan, S., & Verma, S. (2022). Ensemble modeling to predict the impact of future climate change on the global distribution of *Olea europaea* subsp. *Cuspidata*. *Frontiers in Forests and Global Change*, 5, 977691.

- Khatri, P. K., & Barua, K. N. (2011). Structural Composition and Productivity Assessment of The Grassland Community of Kazhiranga National Park, Assam. *Indian Forester*, 137(3), 290.
- Khosravi, R., Hemami, M.-R., & Cushman, S. A. (2019). Multi-scale niche modeling of three sympatric felids of conservation importance in central Iran. *Landscape Ecology*, 34(10), 2451–2467. <https://doi.org/10.1007/s10980-019-00900-0>
- Khyanjeet Gogoi, Junter Nyorak, & Jintu Sarma. (2024). A revisionary study on the genus *Cyrtosia* Blume (Orchidaceae) in Northeast India. *Pleione*, 18(1), 123–134. <https://doi.org/10.26679/pleione.18.1.2024.123-134>
- Knapp, A. K., Briggs, J. M., Hartnett, D. C., & Collins, S. L. (1998). *Grassland dynamics: Long-term ecological research in tallgrass prairie* (Vol. 1). Oxford University Press New York. https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/3355294
- Kraft, J. D., Haukos, D. A., Bain, M. R., Rice, M. B., Robinson, S., Sullins, D. S., Hagen, C. A., Pitman, J., Lautenbach, J., Plumb, R., & Lautenbach, J. (2021). Using Grazing to Manage Herbaceous Structure for a Heterogeneity-Dependent Bird. *The Journal of Wildlife Management*, 85(2), 354–368. <https://doi.org/10.1002/jwmg.21984>
- Krishnan, A. (2021). *Marsh Babbler (Pellorneum palustre), version 2.0*. In *Birds of the World* (S. M. Billerman and M. A. Bridwell, Editors). <https://birdsoftheworld.org/bow/species/marbab2/cur/systematics>
- Kumar, A. (2015). Conservation Issues and Possible Solutions for Sustainability of Faunal Diversity of Arunachal Pradesh. In N. J. Raju, W. Gossel, Al. Ramanathan, & M. Sudhakar (Eds.), *Management of Water, Energy and Bio-resources in the Era of Climate Change: Emerging Issues and Challenges* (pp. 249–265). Springer International Publishing. https://doi.org/10.1007/978-3-319-05969-3_20
- Kumar, A. (2018). Mammals of Arunachal Pradesh, India. In C. Sivaperuman & K. Venkataraman (Eds.), *Indian Hotspots: Vertebrate Faunal Diversity, Conservation and Management Volume 2* (pp. 165–176). Springer Singapore. https://doi.org/10.1007/978-981-10-6983-3_9

- Kumar, S. U., Maini, P. K., Chiaverini, L., Hearn, A. J., Macdonald, D. W., Kaszta, Ž., & Cushman, S. A. (2021). Smoothing and the environmental manifold. *Ecological Informatics*, 66, 101472.
- Kumara, H. N., Babu, S., Rao, G. B., Mahato, S., Bhattacharya, M., Rao, N. V. R., Tamiliniyan, D., Parengal, H., Deepak, D., Balakrishnan, A., & Bilaskar, M. (2022). Responses of birds and mammals to long-established wind farms in India. *Scientific Reports*, 12(1), 1339. <https://doi.org/10.1038/s41598-022-05159-1>
- Kunte, S. V. (1988). Geomorphic analysis of upper Assam Plains and adjoining areas for hydrocarbon exploration. *Journal of the Indian Society of Remote Sensing*, 16(1), 15–28. <https://doi.org/10.1007/BF02992097>
- Lahiri, S., Roy, A., & Fleischman, F. (2022). Grassland conservation and restoration in India: A governance crisis. *Restoration Ecology*, 31. <https://doi.org/10.1111/rec.13858>
- Lanchier, N., & Neuhauser, C. (2006). *A spatially explicit model for competition among specialists and generalists in a heterogeneous environment*. <https://projecteuclid.org/journals/annals-of-applied-probability/volume-16/issue-3/A-spatially-explicit-model-for-competition-among-specialists-and-generalists/10.1214/1050516060000000394.short>
- Langham, G. M., Schuetz, J. G., Distler, T., Soykan, C. U., & Wilsey, C. (2015). Conservation status of North American birds in the face of future climate change. *PloS One*, 10(9), e0135350.
- Lasushe, K.-U., Singh, P. P., Chaudhary, K. L., Choudhury, H., & Upadhaya, K. (2024). Diversity, Biomass and Carbon Stock of Woody Species in Community Reserves of Meghalaya, Northeast India. *International Journal of Ecology and Environmental Sciences*, 50(5), 757–769.
- Lele, A., Arasumani, M., Vishnudas, C. K., Joshi, V., Jathanna, D., & Robin, V. V. (2020). Elevation and landscape change drive the distribution of a montane, endemic grassland bird. *Ecology and Evolution*, 10(14), 7755–7767. <https://doi.org/10.1002/ece3.6500>

- Loss, S. R., Will, T., & Marra, P. P. (2013). Estimates of bird collision mortality at wind facilities in the contiguous United States. *Biological Conservation*, 168, 201–209.
- Luirei, K., & Bhakuni, S. S. (2009). Geomorphic imprints of neotectonic activity along the frontal part of Eastern Himalaya, Pasighat, East Siang District, Arunachal Pradesh. *Journal of the Geological Society of India*, 73(3), 441.
- Magness, D. R., Huettmann, F., & Morton, J. M. (2008). Using Random Forests to Provide Predicted Species Distribution Maps as a Metric for Ecological Inventory & Monitoring Programs. In T. G. Smolinski, M. G. Milanova, & A.-E. Hassanien (Eds.), *Applications of Computational Intelligence in Biology* (Vol. 122, pp. 209–229). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-78534-7_9
- Maji, A. K., Nayak, D. C., Krishna, N. D., Srinivas, C. V., Kamble, K., Reddy, G. P. O., & Velayutham, M. (2001). Soil information system of Arunachal Pradesh in a GIS environment for land use planning. *International Journal of Applied Earth Observation and Geoinformation*, 3(1), 69–77.
- Marcolin, F., Lakatos, T., Gallé, R., & Batáry, P. (2021). Fragment connectivity shapes bird communities through functional trait filtering in two types of grasslands. *Global Ecology and Conservation*, 28, e01687.
- Marques, A. T., Moreira, F., Alcazar, R., Delgado, A., Godinho, C., Sampaio, H., Rocha, P., Sequeira, N., Palmeirim, J. M., & Silva, J. P. (2020). Changes in grassland management and linear infrastructures associated to the decline of an endangered bird population. *Scientific Reports*, 10(1), 15150.
- Marshall, J. (1972). *Handbook of the Birds of India and Pakistan Together with Those of Nepal, Sikkim, Bhutan and Ceylon*. JSTOR. <https://www.jstor.org/stable/4084084>
- Matuoka, M. A., Benchimol, M., de Almeida-Rocha, J. M., & Morante-Filho, J. C. (2020). Effects of anthropogenic disturbances on bird functional diversity: A global meta-analysis. *Ecological Indicators*, 116, 106471.
- May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, 10(16), 8927–8935. <https://doi.org/10.1002/ece3.6592>

- Mayi, Y., Jyrwa, J. D., & Patnaik, S. K. (2023). Monitoring of Land use/land cover changes of Daying Ering Wildlife Sanctuary, Arunachal Pradesh, India, using Remote Sensing and Geographic Information System. *Journal of Applied & Natural Science*, 15(2). <https://www.academia.edu/download/110724339/2493.pdf>
- McCarty, J. P., & Winkler, D. W. (1999). Foraging ecology and diet selectivity of tree swallows feeding nestlings. *The Condor*, 101(2), 246–254.
- McKechnie, A. E., & Wolf, B. O. (2010). Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biology Letters*, 6(2), 253–256. <https://doi.org/10.1098/rsbl.2009.0702>
- Menzies, R. K., Rao, M., & Naniwadekar, R. (2021). Assessing the Status of the Critically Endangered White-bellied Heron *Ardea insignis* in north-east India. *Bird Conservation International*, 31(2), 255–267.
- Merow, C., Smith, M. J., & Silander, J. A. (2013). A practical guide to MaxEnt for modeling species' distributions: What it does, and why inputs and settings matter. *Ecography*, 36(10), 1058–1069. <https://doi.org/10.1111/j.1600-0587.2013.07872.x>
- Miller, J. D., & Thode, A. E. (2007). Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment*, 109(1), 66–80.
- Mineau, P. (2003). Birds and pesticides: Are pesticide regulatory decisions consistent with the protection afforded migratory bird species under the Migratory Bird Treaty Act. *Wm. & Mary Env'tl. L. & Pol'y Rev.*, 28, 313.
- Mineau, P., & Whiteside, M. (2013). Pesticide acute toxicity is a better correlate of US grassland bird declines than agricultural intensification. *PloS One*, 8(2), e57457.
- Monroe, A. P., Edmunds, D. R., Aldridge, C. L., Holloran, M. J., Assal, T. J., & Holloran, A. G. (2021). Prioritizing landscapes for grassland bird conservation with hierarchical community models. *Landscape Ecology*, 36(4), 1023–1038. <https://doi.org/10.1007/s10980-021-01211-z>

- Mota, F. M. M., Heming, N. M., Morante-Filho, J. C., & Talora, D. C. (2022). Amount of bird suitable areas under climate change is modulated by morphological, ecological and geographical traits. *Frontiers in Ecology and Evolution*, 10, 987204.
- Murray, R. G., Popescu, V. D., Palen, W. J., & Govindarajulu, P. (2015). Relative performance of ecological niche and occupancy models for predicting invasions by patchily-distributed species. *Biological Invasions*, 17(9), 2691–2706. <https://doi.org/10.1007/s10530-015-0906-3>
- Narasimmarajan, K., Chetri, D., Ri, C., & Mathai, M. T. (2013). Bird Species of conservation concern along the Brahmaputra river in Assam, Northeast India. *Journal Homepage: Wwww. Wesca. Net*, 8(2). https://www.academia.edu/download/74770854/Bird_Species_of_Conservation_Concern_alo20211117-29840-zpc8aj.pdf
- Narasimmarajan, K., Dhruba Chetri, Chandan Ri, & Manu Thomas Mathai. (2014). *Bird Species of Conservation Concern along the Brahmaputra River in Assam, Northeast India*. <https://scispace.com/papers/bird-species-of-conservation-concern-along-the-brahmaputra-1jlv0gtg3>
- Narwade, S., Kalra, M., Jagdish, R., Varier, D., Satpute, S., Khan, N., Talukdar, G., Mathur, V. B., Vasudevan, K., & Pundir, D. S. (2011). Literature based species occurrence data of birds of northeast India. *ZooKeys*, 150, 407.
- Nath, N. K., Sarkar, P. P., & Machary, K. (2010). Ecological assessment of Hispid Hare in Manas National Park, India. *Final Report on Conservation Leadership Programme, Aaranyak, Assam*, 42. https://www.conservationleadershipprogramme.org/wp-content/uploads/2024/12/FinalReport_HispidHare_NabaKNath.pdf
- Nath, P., Chakrabarti, S., & Mukherjee, S. (2022). Breeding biology of the Oriental Skylark *Alauda gulgula*, Bengal Bush Lark *Mirafra assamica* and Paddyfield Pipit *Anthus rufulus* in agricultural fields of West Bengal, India. *India. J. Asian Ornithol*, 38, 1–8.
- National Institute of Wind Energy. (2023). *India's Wind Potential Atlas at 150m agl* (p. 61).
- Neelam Yania, Purba Jyoti Saikia, Daniel Mize, & Hirendra Nath Sarma. (2021). Avian Diversity in Talle Valley: An endemic Bird area of eastern Himalayan Biodiversity Hot Spot in Lower Subansiri, Arunachal Pradesh, India. *Journal of Bioresources*, 8(1), 75–91. <https://doi.org/10.17605/OSF.IO/5U3RH>

- Nelder, J. A., & Wedderburn, R. W. (1972). Generalized linear models. *Journal of the Royal Statistical Society Series A: Statistics in Society*, 135(3), 370–384.
- Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and Flow Regulation of the World's Large River Systems. *Science*, 308(5720), 405–408. <https://doi.org/10.1126/science.1107887>
- Northrup, J. M., & Wittemyer, G. (2013). Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecology Letters*, 16(1), 112–125. <https://doi.org/10.1111/ele.12009>
- Palash, W., Bajracharya, S. R., Shrestha, A. B., Wahid, S., Hossain, Md. S., Mogumder, T. K., & Mazumder, L. C. (2023). Climate Change Impacts on the Hydrology of the Brahmaputra River Basin. *Climate*, 11(1). <https://doi.org/10.3390/cli11010018>
- Parengal, H., PR, A., Dutta, S., & Joy, A. (2025). Distribution, habitat shift, and conservation needs of Jerdons Babbler (*Chrysomma altirostre*): A study of a vulnerable grassland specialist. *Ornis Hungarica*, 2.
- Parengal, H., PR, A., MR, S., P, H., GC, B., & P, S. (2025). Tropical Riverine Grasslands of the Brahmaputra Basin: A Critical Assessment of Biodiversity Threats, Conservation Challenges, and Management Imperatives. *International Journal of Plant and Environment*, 11.
- Parengal, H., PR, A., PV, K., & Dutta, S. (2025). Climate-Driven Habitat Decline and Fragmentation of a South Asian Grassland Specialist: Ensemble Projections for Jerdon's Babbler Under Future Scenarios. *Available at SSRN 5353099*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5353099
- Patle, G. T., & Libang, A. (2014). Trend analysis of annual and seasonal rainfall to climate variability in North-East region of India. *Journal of Applied and Natural Science*, 6(2), 480.
- Patle, G. T., Libang, A., & Ahuja, S. (2016). Analysis of rainfall and temperature variability and trend detection: A non parametric Mann Kendall test approach. 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), 1723–1727. <https://ieeexplore.ieee.org/abstract/document/7724562/>

- Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540(7633), 418–422.
- Penhallurick, J., & Robson, C. (2009). The generic taxonomy of parrotbills (Aves, Timaliidae). *Forktail*, 25, 137–141.
- Perlut, N. G., Strong, A. M., Donovan, T. M., & Buckley, N. J. (2006). Grassland Songbirds in a Dynamic Management Landscape: Behavioral Responses and Management Strategies. *Ecological Applications*, 16(6), 2235–2247. [https://doi.org/10.1890/1051-0761\(2006\)016%255B2235:GSIADM%255D2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016%255B2235:GSIADM%255D2.0.CO;2)
- Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., & Ferrier, S. (2009). Sample selection bias and presence-only distribution models: Implications for background and pseudo-absence data. *Ecological Applications*, 19(1), 181–197. <https://doi.org/10.1890/07-2153.1>
- Pietz, P. J., & Granfors, D. A. (2000). Identifying predators and fates of grassland passerine nests using miniature video cameras. *The Journal of Wildlife Management*, 71–87.
- Posti, R., & Baruah, D. (2020). Geospatial analysis of fishery resources in west Kameng District of Arunachal Pradesh. *Journal of Krishi Vigyan*, 9(si), 131–136.
- Prabhakaran, S., Sharief, M. U., Parengal, H., Karunakaran, P. V., Kumara, H. N., & Babu, S. (2024). The Relationship Between Landscape Metrics and Human Interventions on the Floristic Structure and Composition of the Community Reserves of Meghalaya, India. *International Journal of Plant and Environment*, 10(04), 73–83.
- Pradhan, N. S., Das, P. J., Gupta, N., & Shrestha, A. B. (2021a). Sustainable management options for healthy rivers in South Asia: The case of Brahmaputra. *Sustainability*, 13(3), 1087.
- Pradhan, N. S., Das, P. J., Gupta, N., & Shrestha, A. B. (2021b). Sustainable management options for healthy rivers in South Asia: The case of Brahmaputra. *Sustainability*, 13(3), 1087.
- Pradhan, N. S., Das, P. J., Gupta, N., & Shrestha, A. B. (2021c). Sustainable management options for healthy rivers in South Asia: The case of Brahmaputra. *Sustainability*, 13(3), 1087.

- Prosser, D. J., Ding, C., Erwin, R. M., Mundkur, T., Sullivan, J. D., & Ellis, E. C. (2018). Species distribution modeling in regions of high need and limited data: Waterfowl of China. *Avian Research*, 9(1), 7. <https://doi.org/10.1186/s40657-018-0099-4>
- Purkayastha, J., Roychoudhury, S., Biswa, B. B., Das, M., & Sengupta, S. (2020). Herpetofaunal Diversity and Conservation Status in Amchang Wildlife Sanctuary of Assam, India. In N. Roy, S. Roychoudhury, S. Nautiyal, S. K. Agarwal, & S. Baksi (Eds.), *Socio-economic and Eco-biological Dimensions in Resource use and Conservation* (pp. 217–223). Springer International Publishing. https://doi.org/10.1007/978-3-030-32463-6_9
- Rahayu, S., Sugiarto, T., Madu, L., & Subagyo, A. (2017). Application of principal component analysis (PCA) to reduce multicollinearity exchange rate currency of some countries in Asia period 2004-2014. *International Journal of Educational Methodology*, 3(2), 75–83.
- Rahmani, A. R. (2012). *Threatened Birds of India, Their Conservation Requirements*. Oxford University Press.
- Rahmani, A. R., Rahman, A., Imran, M., Sangwan, T., Jha, R. R., & Khongsai, N. (2022). Birds of D'Ering Memorial Wildlife Sanctuary, Arunachal Pradesh: Summer Surveys. *International Journal of Ecology and Environmental Sciences*, 48(6), 687–701.
- Rahul, S., & Prakash, O. (2018). Assessment of Wind Energy Potential in Northeastern Cities of India. In R. Bera, S. K. Sarkar, & S. Chakraborty (Eds.), *Advances in Communication, Devices and Networking* (Vol. 462, pp. 191–198). Springer Singapore. https://doi.org/10.1007/978-981-10-7901-6_23
- Rajendra Joshi, Shivaji Chaudhry, Lok Man Singh Palni, & Vaibhav Chandra Mathur. (2014). Avifaunal diversity, distribution and threats in Dibru-Saikhowa Biosphere Reserve North-East India Assam (India): A review. *Archives of Applied Science Research*, 6(5), 113–124.

- Rana, S. K., Lindstrom, J., Lehrer, M. A., Ahlering, M., & Hamilton, J. (2025). Forecasting hotspots of climatic suitability for grassland restoration under climate change in North America. *Biological Conservation*, 302, 110988.
- Rather, T. A., Kumar, S., & Khan, J. A. (2020). Multi-scale habitat modelling and predicting change in the distribution of tiger and leopard using random forest algorithm. *Scientific Reports*, 10(1), 11473.
- Ravi, R., & Krishnan, S. (2024). Invasive networks: An environmental history of the introduction of *Prosopis juliflora* to Banni grassland, India. *Geoforum*, 157, 104144.
- Rawat, G. S., & Adhikari, B. S. (2015). Ecology and management of grassland habitats in India. *ENVIS Bulletin: Wildlife & Protected Areas*, 17.
- Reino, L., Beja, P., Araújo, M. B., Dray, S., & Segurado, P. (2013). Does local habitat fragmentation affect large-scale distributions? The case of a specialist grassland bird. *Diversity and Distributions*, 19(4), 423–432. <https://doi.org/10.1111/ddi.12019>
- Rheindt, F. E., Tizard, R., Pwint, N., & Lin, N. (2014a). The rediscovery of Myanmar's Jerdon's Babbler *Chrysomma altirostre altirostre*. *BirdingASIA*, 22, 13–15.
- Rheindt, F. E., Tizard, R., Pwint, N., & Lin, N. (2014b). The rediscovery of Myanmar's Jerdon's Babbler *Chrysomma altirostre altirostre*. *BirdingASIA*, 22, 13–15.
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., & Fricko, O. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168.
- Ribic, C. A., Koford, R. R., Herkert, J. R., Johnson, D. H., Niemuth, N. D., Naugle, D. E., Bakker, K. K., Sample, D. W., & Renfrew, R. B. (2009). Area sensitivity in North American grassland birds: Patterns and processes. *The Auk*, 126(2), 233–244.
- Ries, L., Fletcher, R. J., Battin, J., & Sisk, T. D. (2004). Ecological Responses to Habitat Edges: Mechanisms, Models, and Variability Explained. *Annual Review of Ecology, Evolution, and Systematics*, 35(1), 491–522. <https://doi.org/10.1146/annurev.ecolsys.35.112202.130148>

- Robbins, M. B., & Dale, B. C. (1999). Sprague's Pipit(*Anthus spragueii*). *The Birds of North America*, 439, 16.
- Robson, C. (2020). *Field guide to the birds of South-East Asia*. Bloomsbury Publishing.
- Rosenberg, K., Francis, C., Berlanga, H., Scarl, J., & Coordinator, U. S. N. (2016). *The State of North America's Birds 2016*.
- Rosenberg, K. V., Dokter, A. M., Blancher, P. J., Sauer, J. R., Smith, A. C., Smith, P. A., Stanton, J. C., Panjabi, A., Helft, L., Parr, M., & Marra, P. P. (2019). Decline of the North American avifauna. *Science*, 366(6461), 120–124. <https://doi.org/10.1126/science.aaw1313>
- Rotenberry, J. T., & Wiens, J. A. (1991). Weather and Reproductive Variation in Shrubsteppe Sparrows: A Hierarchical Analysis. *Ecology*, 72(4), 1325–1335. <https://doi.org/10.2307/1941105>
- Roy, A., Banerjee, S., Uddin, M., Jhala, Y., & Dutta, S. (2025). Bird mortality at wind farms in a tropical desert. *Scientific Reports*, 15(1), 19221.
- Saalfeld, D. T., Saalfeld, S. T., Conway, W. C., & Hartke, K. M. (2016). Wintering grassland bird responses to vegetation structure, exotic invasive plant composition, and disturbance regime in coastal prairies of Texas. *The Wilson Journal of Ornithology*, 128(2), 290–305.
- Sadanandan, K. R., Olsson, U., Tizard, R., Khan, A. A., Thet Zaw Naing, Naing Lin, Nila Pwint, & Rheindt, F. E. (2018). Genetic and biometric variation across the fragmented range of Jerdon's Babbler, *Chrysomma altirostre*, a threatened Oriental grassland specialist. *Journal of Ornithology*, 159(2), 575–579. <https://doi.org/10.1007/s10336-018-1530-7>
- Saeed, U., Das, R., Ali, S. Z., Mani, A., Badola, R., & Hussain, S. A. (2025). Evolving landscapes: Long term land use and climate-induced changes in the Brahmaputra floodplain, India. *Frontiers in Environmental Science*, 13, 1550450.
- Saikia, A. (2011). *Forests and ecological history of Assam, 1826–2000*. Oxford University Press.

- Saikia, P., Deka, J., Bharali, S., Kumar, A., Tripathi, O. P., Singha, L. B., Dayanandan, S., & Khan, M. L. (2017). Plant diversity patterns and conservation status of eastern Himalayan forests in Arunachal Pradesh, Northeast India. *Forest Ecosystems*, 4(1), 28. <https://doi.org/10.1186/s40663-017-0117-8>
- Salafsky, N., Boshoven, J., Burivalova, Z., Dubois, N. S., Gomez, A., Johnson, A., Lee, A., Margoluis, R., Morrison, J., Muir, M., Pratt, S. C., Pullin, A. S., Salzer, D., Stewart, A., Sutherland, W. J., & Wordley, C. F. R. (2019). Defining and using evidence in conservation practice. *Conservation Science and Practice*, 1(5). <https://doi.org/10.1111/csp2.27>
- Samson, F. B., Knopf, F. L., & Ostlie, W. R. (2004). Great Plains ecosystems: Past, present, and future. *Wildlife Society Bulletin*, 32(1), 6–15. [https://doi.org/10.2193/0091-7648\(2004\)32%255B6:GPEPPA%255D2.0.CO;2](https://doi.org/10.2193/0091-7648(2004)32%255B6:GPEPPA%255D2.0.CO;2)
- Samson, F., & Knopf, F. (1994). Prairie conservation in north america. *BioScience*, 44(6), 418–421.
- SANDEEP, A., VH, A., & DAS, S. (2023). *On the variability and climatology of Arunachal Pradesh: An observational study*. <https://www.researchsquare.com/article/rs-3494926/latest>
- Saranya, K. R. L., Lakshmi, T. V., & Reddy, C. S. (2021). Predicting the potential sites of *Chromolaena odorata* and *Lantana camara* in forest landscape of Eastern Ghats using habitat suitability models. *Ecological Informatics*, 66, 101455.
- Sarkar, S., Pressey, R. L., Faith, D. P., Margules, C. R., Fuller, T., Stoms, D. M., Moffett, A., Wilson, K. A., Williams, K. J., Williams, P. H., & Andelman, S. (2006). Biodiversity Conservation Planning Tools: Present Status and Challenges for the Future. *Annual Review of Environment and Resources*, 31(1), 123–159. <https://doi.org/10.1146/annurev.energy.31.042606.085844>
- Sarma, J. N. (2005). Fluvial process and morphology of the Brahmaputra River in Assam, India. *Geomorphology*, 70(3–4), 226–256.

- Sarma, P., Boruah, P. A., & Buragohain, R. (2023). MED 117: A dataset of medicinal plants mostly found in Assam with their leaf images, segmented leaf frames and name table. *Data in Brief*, 47, 108983.
- Sauer, J. R., Niven, D. K., Hines, J. E., Ziolkowski Jr, D. J., Pardieck, K. L., Fallon, J. E., & Link, W. A. (2017). The North American breeding bird survey, results and analysis 1966–2015. Version 2.07. 2017. *US Geological Survey Patuxent Wildlife Research Center, Laurel, Maryland, USA*.
- Sauer, J. R., Pardieck, K. L., Ziolkowski Jr, D. J., Smith, A. C., Hudson, M.-A. R., Rodriguez, V., Berlanga, H., Niven, D. K., & Link, W. A. (2017). The first 50 years of the North American breeding bird survey. *The Condor: Ornithological Applications*, 119(3), 576–593.
- Savary, P., Clauzel, C., Foltête, J.-C., Vuidel, G., Girardet, X., Bourgeois, M., Martin, F.-M., Ropars, L., & Garnier, S. (2024). Multiple habitat graphs: How connectivity brings forth landscape ecological processes. *Landscape Ecology*, 39(9), 168. <https://doi.org/10.1007/s10980-024-01947-4>
- Scheiman, D. M., Bollinger, E. K., & Johnson, D. H. (2003). Effects of leafy spurge infestation on grassland birds. *The Journal of Wildlife Management*, 115–121.
- Şekercioğlu, Ç. H., Primack, R. B., & Wormworth, J. (2012). The effects of climate change on tropical birds. *Biological Conservation*, 148(1), 1–18.
- Selvan, M., Lyngdoh, S., Gopi, G. V., & Habib, B. (2014). Density estimation of leopard cat *Prionailurus bengalensis* using capture-recaptures sampling in lowland forest of Pakke Tiger Reserve, Arunachal Pradesh, India. *Mammalia*, 78(4). <https://doi.org/10.1515/mammalia-2013-0084>
- Shaffer, J. A., Igl, L. D., Johnson, D. H., Sondreal, M. L., Goldade, C. M., Zimmerman, A. L., Wooten, T. L., & Euliss, B. R. (2023). *The effects of management practices on grassland birds—Bobolink (Dolichonyx oryzivorus)*. US Geological Survey. <https://pubs.usgs.gov/publication/pp1842LL>

- Shah, R. K., & Dutta, M. (2024). Spatial distribution and characteristics of wetlands in Dibrugarh district, Assam: A GIS based approach. *Proceedings of the Indian National Science Academy*. <https://doi.org/10.1007/s43538-024-00383-x>
- Sharma, M., Devi, A., Badola, R., Sharma, R. K., & Hussain, S. A. (2023). Impact of management practices on the tropical riverine grasslands of Brahmaputra floodplains: Implications for conservation. *Ecological Indicators*, 151, 110265. <https://doi.org/10.1016/j.ecolind.2023.110265>
- Sharmah, D., & Jha, D. K. (2014). Diversity of Arbuscular Mycorrhizal Fungi in Disturbed and Undisturbed Forests of Karbi Anglong Hills of Assam, India. *Agricultural Research*, 3(3), 229–238. <https://doi.org/10.1007/s40003-014-0110-1>
- Showler, D. A., & Davidson, P. (1999). Observations of Jerdon's Babbler *Chrysomma altirostre* and Rufous-vented Prinia *Prinia burnesii* in Punjab and North-west Frontier Provinces, Pakistan. *Forktail*, 67–76.
- Siddhartha Suman Bora, Lakhijyoti Saikia, Jyotimoiee Hatiboruah, & Partha Pratim Bora. (2024). Assessment of Migratory Bird Diversity in Key Wetlands and Forest Reserves of Lakhimpur District, Assam, India. *Uttar Pradesh Journal of Zoology*, 45(19), 254–269. <https://doi.org/10.56557/upjz/2024/v45i194525>
- Sinha, A., Kumar, R. S., Gama, N., Madhusudan, M. D., & Mishra, C. (2006). Distribution and conservation status of the Arunachal macaque, *Macaca munzala*, in western Arunachal Pradesh, northeastern India. *Primate Conservation*, 2006(21), 145–148.
- Sinha, A., Talukdar, S., Das, G. C., Sarma, P. K., & Singha, H. (2012). Diversity of winter avifauna in Dheer beel, Assam, India. *Indian Birds*, 10, 99–103.
- Skagen, S. K., Augustine, D. J., & Derner, J. D. (2018). Semi-arid grassland bird responses to patch-burn grazing and drought. *The Journal of Wildlife Management*, 82(2), 445–456. <https://doi.org/10.1002/jwmg.21379>
- Skowno, A. L., & Bond, W. J. (2003). Bird community composition in an actively managed savanna reserve, importance of vegetation structure and vegetation composition. *Biodiversity & Conservation*, 12(11), 2279–2294. <https://doi.org/10.1023/A:1024545531463>

- Talbot, C. J., Bennett, E. M., Cassell, K., Hanes, D. M., Minor, E. C., Paerl, H., Raymond, P. A., Vargas, R., Vidon, P. G., Wollheim, W., & Xenopoulos, M. A. (2018). The impact of flooding on aquatic ecosystem services. *Biogeochemistry*, 141(3), 439–461. <https://doi.org/10.1007/s10533-018-0449-7>
- Taro, K. (2021). Biodiversity of Arunachal Pradesh and its Conservation. *Dera Natung Government College Research Journal*, 6(1), 79–85.
- Thakur, M., Kalita, J., Brahma, N., Rajbongshi, K., Bhattacharyya, K., Sarmah, A. C., Sinha, A., Dutta, D. K., Das, D., & Lahkar, B. P. (2024). Current conservation status of Bengal Florican *Houbaropsis bengalensis* in Manas National Park, Assam, India. *Journal of Threatened Taxa*, 16(7), 25507–25515.
- Thapa, G. J., Wikramanayake, E., & Forrest, J. (2015). *Climate-change impacts on the biodiversity of the Terai Arc Landscape and the Chitwan-Annapurna Landscape*. by WWF Nepal, Hariyo Ban Program PO Box: 7660 Baluwatar, Kathmandu, Nepal T https://wwfasia.awsassets.panda.org/downloads/ccva_final_3.pdf
- Thuiller, W., Georges, D., Engler, R., & Breiner, F. (2014). biomod2: Ensemble platform for species distribution modeling. R package version 3.1-64. *Availabl at: Http://CRANR-Projectorg/Package= Biomod2 (Accessed February 2015)*.
- Thuiller, W., Lafourcade, B., Engler, R., & Araújo, M. B. (2009). BIOMOD – a platform for ensemble forecasting of species distributions. *Ecography*, 32(3), 369–373. <https://doi.org/10.1111/j.1600-0587.2008.05742.x>
- Trivedi, M., Arekar, K., Manu, S., Kuderna, L. F. K., Rogers, J., Farh, K. K., Bonet, T. M., & Umapathy, G. (2025). Historical Demography and Species Distribution Models Shed Light on Speciation in Primates of Northeast India. *Ecology and Evolution*, 15(2), e70968. <https://doi.org/10.1002/ece3.70968>
- Valavi, R., Elith, J., Lahoz-Monfort, J. J., & Guillera-Arroita, G. (2021). Modelling species presence-only data with random forests. *Ecography*, 44(12), 1731–1742. <https://doi.org/10.1111/ecog.05615>

- Valavi, R., Guillera-Arroita, G., Lahoz-Monfort, J. J., & Elith, J. (2022). Predictive performance of presence-only species distribution models: A benchmark study with reproducible code. *Ecological Monographs*, 92(1), e01486. <https://doi.org/10.1002/ecm.1486>
- van Oorschot, M., Kleinhans, M., Buijse, T., Geerling, G., & Middelkoop, H. (2018). Combined effects of climate change and dam construction on riverine ecosystems. *Ecological Engineering*, 120, 329–344.
- Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, 109(1–2), 5–31. <https://doi.org/10.1007/s10584-011-0148-z>
- Vasudev, D., Goswami, V. R., Srinivas, N., Syiem, B. L. N., & Sarma, A. (2021). Identifying important connectivity areas for the wide-ranging Asian elephant across conservation landscapes of Northeast India. *Diversity and Distributions*, 27(12), 2510–2526. <https://doi.org/10.1111/ddi.13419>
- Villar-Hernández, B. de J., Pérez-Rodríguez, P., & Souza, A. de. (2024). Long temporal trend and seasonal variation analysis of forest fires in Brazilian biomes: A stochastic approach. *Revista Mexicana de Ciencias Forestales*, 15(84), 29–53.
- Walia, C. S., & Chamuah, G. S. (1992). Flood affected soils of Brahmaputra valley and their suitability for land use planning. *Journal of the Indian Society of Soil Science*, 40(2), 335–340.
- Wilcox, C., Van Seville, E., & Hardesty, B. D. (2015). Threat of plastic pollution to seabirds is global, pervasive, and increasing. *Proceedings of the National Academy of Sciences*, 112(38), 11899–11904. <https://doi.org/10.1073/pnas.1502108112>
- With, K. A., King, A. W., & Jensen, W. E. (2008). Remaining large grasslands may not be sufficient to prevent grassland bird declines. *Biological Conservation*, 141(12), 3152–3167.
- Xeno-canto. (2025a). *Black-breasted Parrotbill (Paradoxornis flavirostris): Xeno-canto*. <https://xeno-canto.org/species/Paradoxornis-flavirostris>

- xeno-canto. (2025). *Jerdon's Babbler (Chrysomma altirostre)*: Xeno-canto. <https://xeno-canto.org/species/Chrysomma-altirostre>
- Xeno-canto. (2025b). *Marsh Babbler (Pellorneum palustre)*: Xeno-canto. <https://xeno-canto.org/species/Pellorneum-palustre>
- Yan, H., & Liu, G. (2021). Fire's effects on grassland restoration and biodiversity conservation. *Sustainability*, 13(21), 12016.
- Zhuo, Z., Xu, D., Pu, B., Wang, R., & Ye, M. (2020). Predicting distribution of *Zanthoxylum bungeanum* Maxim. in China. *BMC Ecology*, 20(1), 46. <https://doi.org/10.1186/s12898-020-00314-6>
- Zuckerberg, B., Ribic, C. A., & McCauley, L. A. (2018). Effects of temperature and precipitation on grassland bird nesting success as mediated by patch size. *Conservation Biology*, 32(4), 872–882. <https://doi.org/10.1111/cobi.13089>

Publications

Distribution, habitat shift, and conservation needs of Jerdon’s Babbler (*Chrysomma altirostre*): A study of a vulnerable grassland specialist

Harif PARENGAL^{1,2,3*}, Padijarevedu Ramachandran ARUN^{1,3},
Sarbasis DUTTA^{1,2,4} & Anisha JOY²

Received: November 26, 2024 – Revised: April 25, 2025 – Accepted: April 27, 2025



Parengal, H., Arun, P. R., Dutta, S. & Joy, A. 2025. Distribution, habitat shift, and conservation needs of Jerdon’s Babbler (*Chrysomma altirostre*): A study of a vulnerable grassland specialist. – Ornis Hungarica 33(2): 224–237. DOI: 10.2478/orhu-2025-0030

Abstract Grassland ecosystems are vital for global biodiversity but are increasingly threatened by habitat loss, agricultural expansion, urbanization, and climate change. Jerdon’s Babbler (*Chrysomma altirostre*), a vulnerable grassland specialist, serves as a model species to assess the impacts of habitat degradation and fragmentation. This study analysed historical and current distributions, revealing a significant contraction from 326,263 km² to 173,071 km², representing a 47% reduction in the species’ historical range. The overlap between historical and current ranges was limited to 71,623 km², while 101,448 km² of new areas were identified as potential habitat gain, indicating possible range shifts. The centroids of the distributions of the three subspecies shifted significantly: Indian and Saharo-Sindian subspecies moved northeast by 361 km and 444 km, respectively, while the Burmese subspecies shifted 490 km south. Populations in the Indo-Bangladesh region remain uncertain due to a lack of recent records. These findings underscore extensive habitat loss, reduced connectivity, and the persistence of fragmented populations primarily within protected areas. Conservation priorities include grassland restoration, habitat connectivity enhancement, and mitigating disturbances such as unauthorized playback and seasonal fires. While Jerdon’s Babbler exhibits adaptability to degraded habitats, its long-term viability remains uncertain without targeted interventions. This study highlights the necessity of expanded conservation efforts to safeguard populations beyond protected zones and to preserve this species as an indicator of grassland ecosystem health.

Keywords: kernel density, temporal distribution, niche dynamics, climate change, grassland ecosystems

Összefoglalás A füves területek létfontosságúak a globális biológiai sokféleség szempontjából, de az élőhelyek elvesztése, a mezőgazdaság terjeszkedése, az urbanizáció és az éghajlatváltozás egyre inkább veszélyezteti őket. A Jerdon-tímália (*Chrysomma altirostre*), a füves területek sérülékeny specialista madárfaja szolgál modellként az élőhelyek pusztulásának és feldarabolódásának értékeléséhez. A szerzők tanulmányukban elemezték a faj történelmi és a jelenlegi elterjedését. A faj elterjedési területének kiterjedése 47%-os csökkenést mutatott, 326 263 km²-ről 173 071 km²-re esett vissza. A történelmi és a jelenlegi elterjedési terület közötti átfedés 71 623 km²-re korlátozódott, míg 101 448 km²-nyi potenciálisan új élőhelyen jelent meg a faj. Ez az elterjedési terület áthelyeződésére utalhat. Az alfajok elterjedésének központjai jelentősen, az indiai 361, a burmai 490, míg a sahara-szindiai 444 km-rel eltolódtak. Az indo-bangladesi régió populációinak helyzete bizonytalan maradt, mivel nincsenek friss feljegyzések. Megállapításaik hangsúlyozzák az élőhelyek nagymértékű csökkenését és ezek elszigetelődését. Az elszigetelt populációk fennmaradása elsősorban a védett területeken belül lehetséges. A természetvédelmi prioritások közé tartozik a gyepterületek helyreállítása, az élőhelyek folytonosságának biztosítása, valamint az olyan zavaró tényezők mérséklése, mint az engedély nélküli hívóhang lejátszás és a szezonális tüzek. Bár a Jerdon-tímália képes alkalmazkodni a leromlott élőhelyekhez, hosszú távú fennmaradása célzott beavatkozások nélkül bizonytalan marad. Ez a tanulmány rávilágít a védett területeken kívüli populációk megőrzését célzó, kiterjesztett védelmi erőfeszítések szükségességére.

Tropical Riverine Grasslands of the Brahmaputra Basin: A Critical Assessment of Biodiversity Threats, Conservation Challenges, and Management Imperatives

Harif Parengal^{1,2,3}, Padijareveedu Ramachandran Arun^{1,3*}, Sethu Madhav Reghu^{2,4}, Haris Parengal², Bency Gertrude Choyikandi², Sumayyabi Palliveedu²
DOI: 10.18811/ijpen.v11i03.00

ABSTRACT

The Brahmaputra grasslands, stretching across the floodplains of Assam and adjoining regions of Bhutan, represent one of South Asia's most ecologically vital and biodiverse tropical riverine ecosystems. This review presents a comprehensive synthesis of existing literature alongside insights from our recent field investigations, which corroborate many of the findings reported in earlier studies. By analysing peer-reviewed publications, government reports, and field data, we outline the distinctive ecological features of these grasslands, their exceptional biodiversity, including critically endangered bird species such as the Yellow-breasted Bunting (*Emberiza aureola*), White-bellied Heron (*Ardea insignis*), and Manipur Bush-Quail (*Perdichamanipurensis*). Flagship species such as the Bengal tiger (*Panthera tigris*) and the greater one-horned rhinoceros (*Rhinoceros unicornis*) are facing numerous pressing conservation threats. These threats include altered fire regimes, biological invasions, overgrazing, encroachment by woody vegetation, and changes in soil conditions. Although conservation efforts in protected areas like Kaziranga and Manas have shown encouraging results, large portions of the grasslands remain vulnerable due to habitat fragmentation, climate change, ongoing human-wildlife conflict, and anthropogenic activities. Our fieldwork confirms these patterns and has been compiled in alignment with existing scientific evidence. Furthermore, this synthesis highlights several critical gaps, including the lack of long-term ecological monitoring, an inadequate understanding of grassland-specific management needs, and limited incorporation of community-based conservation approaches. The review offers a foundational framework for developing evidence-based strategies aimed at conserving tropical riverine grasslands. It underscores the pressing need for targeted management protocols tailored to the unique ecological dynamics of the Brahmaputra grasslands. To effectively address these challenges, we advocate for enhanced transboundary cooperation, the adoption of participatory, community-led management models, and the integration of advanced tools such as environmental DNA (eDNA) analysis and remote sensing technologies within adaptive conservation frameworks. These measures are essential to promoting the long-term resilience and ecological sustainability of these critical habitats.

Highlight:

- Riverine Grasslands' major threats include habitat fragmentation, overgrazing, altered fire regimes, invasive species, and climate change.
- While protected zones like Kaziranga and Manas show positive trends, large unprotected grassland areas remain highly at risk.
- There is a lack of long-term monitoring, a poor understanding of grassland-specific needs, and limited community involvement in conservation.
- Urgent, grassland-specific conservation with community involvement, cross-border collaboration, and landscape-scale planning is essential to avert collapse.

Keywords: Brahmaputra grasslands, Biodiversity conservation, Tropical riverine ecosystems, Endangered species, Habitat management
International Journal of Plant and Environment (2025); ISSN: 2454-1117 (Print), 2455-202X (Online)

INTRODUCTION

Grasslands are one of the Earth's dominant biomes, covering up to 40% of the planet's terrestrial surface (DiPaolo, 2020; Gibson, 2009; White *et al.*, 2000), yet their conservation value remains significantly underappreciated compared to forests (Bardgett *et al.*, 2021). The Brahmaputra grasslands of northeastern India and southern Bhutan represent a unique tropical riverine grassland ecosystem of global conservation importance (Sharma *et al.*, 2023a). These grasslands, characterized by their location in the floodplains of the mighty Brahmaputra River, support exceptional biodiversity and provide critical ecosystem services to millions of people (Sharma *et al.*, 2023a).

The Brahmaputra River system creates unique alluvial grasslands across its 2,900-kilometer journey from the Tibetan Plateau to the Bay of Bengal (Kumar and Ambastha, 2016). The Brahmaputra grasslands extend across multiple protected areas in Assam, India, including Kaziranga National Park (UNESCO, 2023), Manas National Park (UNESCO, 2025), Orang National Park, Dibru-Saikhowa National Park, and D'Ering Wildlife Sanctuary

¹Salim Ali Centre for Ornithology and Natural History (SACON), South India Centre of Wildlife Institute of India, Anaikatty, Tamil Nadu-641108, India

²Centre for Tropical Biodiversity Conservation (CTBC), Malappuram - 676504, India

³Bharathiar University, Coimbatore - 641046, India

⁴Marine Biology Laboratory, Department of Marine Biosciences, Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies, Panangad, Kochi, Kerala, India

***Corresponding author:** Arun, P. R. affiliation, Email: eiasacon@gmail.com

How to cite this article: Parengal, H., Arun, P.R., Reghu, S.M., Parengal, H., Choyikandi, B.G., Palliveedu, S. (2025). Tropical Riverine Grasslands of the Brahmaputra Basin: A Critical Assessment of Biodiversity Threats, Conservation Challenges, and Management Imperatives. *International Journal of Plant and Environment*. 11(3), 1-4.

Submitted: 26/07/2025 **Accepted:** 11/09/2025 **Published:** 00/00/2025

Distribution patterns of the Marsh Babbler (*Pellorneum palustre*) in Brahmaputra grasslands: An integrated citizen science approach

Harif Parengal ^{1,2,3}, Arun, P. R ^{1,3*}, Ashiya Salim ¹

¹Sálim Ali Centre for Ornithology and Natural History, South India Centre of Wildlife Institute of India, Anaikatty, Tamil Nadu-641108, India, ²Centre for Tropical Biodiversity Conservation, Malappuram - 676504, India, ³Bharathiar University, Coimbatore - 641046, India

ABSTRACT

introduction: The Marsh Babbler (*Pellorneum palustre*) is a vulnerable, endemic species confined to the Brahmaputra floodplain grasslands of northeastern India and eastern Bangladesh. Which represent a critically important endemic species within the Brahmaputra floodplain ecosystem, yet its distribution patterns remain poorly understood due to limited systematic surveys. **Methods:** This study analyses the spatial distribution patterns of Marsh Babbler occurrence records using an integrated citizen science approach, combining data from multiple platforms including eBird, iNaturalist, GBIF, and field surveys. We compiled 337 unique occurrence records spanning from 2018-2024 across the species' range and applied spatial statistical methods to examine clustering patterns and spatial autocorrelation. **Result and Discussion:** Results showed significant spatial clustering (Clark-Evans $R = 0.094$, $p < 2.2 \times 10^{-16}$) and positive spatial autocorrelation (Moran's $I = 0.115$, $p = 7.2 \times 10^{-6}$), indicating non-random distribution patterns across the landscape. eBird contributed the majority of records (85.8%), followed by survey data (5.6%), iNaturalist (4.5%), and other sources. Local indicators of spatial association (LISA) revealed significant clustering hotspots, particularly in areas with intensive birding activity. Our findings demonstrate the value of integrating multiple citizen science platforms for understanding the distribution of rare, endemic species while highlighting potential biases inherent in opportunistic data collection. These results provide crucial baseline information for conservation planning and monitoring of this vulnerable grassland specialist.



ARTICLE TYPE

Research Article

ARTICLE HISTORY

Received 12 February 2025
Accepted 26 June 2025

KEYWORDS

Pellorneum palustre,
citizen science,
Brahmaputra grasslands,
conservation biology,
Moran's I

VOLUME

Volume No. 01

Introduction

The Brahmaputra floodplains represent one of Asia's most dynamic and biologically significant grassland ecosystems, supporting exceptional avian diversity including several endemic and threatened species (Kumar, 2018). Among these, the Marsh Babbler (*Pellorneum palustre*) stands as a flagship species for grassland conservation, being entirely endemic to the Brahmaputra basin and its associated tributaries across Assam, Arunachal Pradesh, and eastern Bangladesh (Rasmussen & Anderton, 2005). Current IUCN assessments classify this species as Vulnerable with a declining population trend, estimating only 10,000-19,999 individuals remaining across its entire range (BirdLife International, 2024). The species faces unprecedented threats from habitat conversion, agricultural intensification, inappropriate grassland management, and increasingly frequent flood events associated with climate change and catchment degradation (Dias et al., 2016; Masood et al., 2015; Wang et al., 2023).

Traditional ornithological surveys in the Brahmaputra region have been hampered by challenging terrain, seasonal accessibility constraints, and limited research infrastructure (Choudhury, A, 2000). The emergence of citizen science platforms offers unprecedented opportunities to overcome these limitations through crowd-sourced biodiversity data collection (Sullivan et al., 2009). eBird, managed by the Cornell Lab of Ornithology, has become the world's largest biodiversity citizen science project, providing structured occurrence data with associated effort metrics and robust data quality protocols (Fink et al., 2020; Kelling et al., 2015). iNaturalist contributes research-grade observations verified through community consensus, particularly valuable for cryptic species requiring photographic documentation (Di Cecco et al., 2021). The Global Biodiversity Information Facility (GBIF) serves as an integrated repository accessing data from both platforms alongside museum collections and scientific surveys, utilizing standardized data formats that enable large-scale biodiversity analyses (Wieczorek et al., 2012).

Despite the critical conservation status of Marsh Babbler and the increasing availability of citizen science data, no comprehensive analysis of its distribution patterns has been conducted using these modern data sources. Previous knowledge relies primarily on historical accounts in classic ornithological works (Ali & Ripley, 1983; Baker, 1922; Grimmett et al., 2016) and regional surveys (Choudhury, A, 2000), limiting understanding of seasonal habitat preferences, population connectivity, and responses to landscape changes. Recent research in the Brahmaputra grasslands has focused on microhabitat requirements of grassland bird communities (Zhang et al., 2022) and habitat management impacts (Wang et al., 2023), but specific studies on endemic species like the Marsh Babbler remain absent from the literature.

The integration of multi-platform citizen science data offers potential to fill these knowledge gaps while providing baseline information essential for evidence-based conservation planning (Matutini et al., 2021; Robinson et al., 2018). Recent frameworks for leveraging citizen science data in Indian bird conservation demonstrate the potential for such approaches to inform national and regional conservation strategies (Viswanathan et al., 2025). Climate change projections for the Ganges-Brahmaputra-Meghna basin indicate increasing hydrological variability and potential shifts in seasonal flooding patterns (Masood et al., 2015), making urgent the need for comprehensive baseline data on habitat-specialist species. Additionally, continued wetland degradation documented across the region (Bhatta et al., 2016) further emphasizes the conservation importance of understanding current

CONTACT

Arun, P. R,  Sálim Ali Centre for Ornithology and Natural History, South India Centre of Wildlife Institute of India, Anaikatty, Tamil Nadu-641108, India  eiasacon@gmail.com

© 2025 The Author(s). This article is published by SciFoliage Publishing under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>). This license permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. In accordance with these terms, the Accepted Manuscript may be deposited in a repository by the author(s) or with their consent.

The Relationship Between Landscape Metrics and Human Interventions on the Floristic Structure and Composition of the Community Reserves of Meghalaya, India

Sandeep Prabhakaran^{1,2}, Sharief M.U.^{1*}, Harif Parengal^{2,3}, Karunakaran P.V.², Kumara H.N.² and Babu S.²

DOI: 10.18811/ijpen.v10i04.08

ABSTRACT

Community Reserves (CRs) are a unique category of protected areas managed by local communities, playing a crucial role in biodiversity conservation. However, the impact of landscape metrics and human intervention on vegetation in these reserves remains less explored. This study examines the relationship between landscape structure, human interventions, and vegetation in 30 CRs across Meghalaya, India, each associated with local villages and clans. Vegetation data were collected using stratified random sampling techniques, and indices such as Shannon, Simpson, and Evenness were calculated. For spatial analysis, Sentinel-2 imagery was utilized, with land use and land cover classification to gather landscape information by using the QGIS tool. The classified data were further analyzed using landscape metrics in FRAGSTAT software. The data on vegetation composition, landscape metrics, and the human disturbance index were then analyzed for correlations. Canonical Correspondence Analysis (CCA) was performed using R software to explore these relationships. Plant diversity varied significantly, with Shannon indices ranging from 2.147 (Mikadogre CR) to 3.845 (Kur Pyrtuh CR). Simpson indices were generally high (>0.8), indicating low species dominance. Evenness ranged from 0.153 (Sakalgre CR) to 0.557 (Kur Pyrtuh CR). The human intervention index varied from 0 (e.g., Chyrmang CR) to 6 (e.g., Jirang CR), with most reserves showing low to moderate levels of disturbance. CCA analysis revealed that 69.08% of the variation in diversity indices is strongly associated with landscape metrics (Total area, Number of Patches, Patch Density, Least Patch Index, Total Edge, Edge Density, Least Shape Index, Area Mean, Area Range, Landscape Division Index, Effective Mesh Size, Splitting Index, Patch Richness) and human intervention. The results suggest that CRs with more complex patch shapes tend to support higher plant species diversity. These findings have significant implications for CR management.

Keywords: Meghalaya, Community conservation, Floristic diversity, LULC classification, Past management regime.

Highlights:

- Meghalaya has the second-largest number of community reserves in India, but many remain unexplored due to their inaccessibility.
- This study examined 30 community reserves, the highest number ever included in a single research effort in the region.
- It offers an in-depth understanding of the relationship between landscape metrics, human interventions, and the floristic structure and composition of Meghalaya's Community Reserve.
- This study helps to the policymakers and stakeholders to improve the conservation practices in each community reserve in Meghalaya.
- Advanced tools such as GIS, FRAGSTATS, and R statistical packages were utilized to conduct the research.

International Journal of Plant and Environment (2024);

ISSN: 2454-1117 (Print), 2455-202X (Online)

INTRODUCTION

Forests play an important role in the socio-economic scenario of India and the rural communities have conserved forest patches since ancient times (Paul and Chakrabarti, 2011; Basu and Debnath, 2023). These forests act as an integral part of the life of rural communities, which provide food, fuel, and fodder and are considered essential for their physical and cultural survival (Madegowda and Rao, 2017). Community Reserves (CRs), established through the Wildlife (Protection) Amendment Act 2002, are a more recent addition to India's protected area categories. These areas are managed by local communities in association with the forest department, often involving private or communal land holdings (WLPAA 2002). CRs play a significant role in conserving biodiversity-rich forest patches in Northeast India, where most land is owned and managed by local communities or clans (Dikshit and Dikshit, 2014). The state of Meghalaya has the second-highest number of CRs in India,

^{1*}Botanical Survey of India Southern Regional Centre, Coimbatore, Tamil Nadu

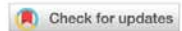
²Salim Ali Centre for Ornithology and Natural History South India Centre of Wildlife Institute of India, Coimbatore, Tamil Nadu

³Centre for Tropical Biodiversity Conservation, Malappuram, Kerala

***Corresponding author:** Sharief M.U., Botanical Survey of India Southern Regional Centre, Coimbatore, Tamil Nadu, Email: shariefbsi@yahoo.co.in

How to cite this article: Sandeep , P., Sharief, M.U., Harif, P., Karunakaran, P.V., Kumara, H.N., Babu, S. (2024). The Relationship Between Landscape Metrics and Human Interventions on the Floristic Structure and Composition of the Community Reserves of Meghalaya, India. *International Journal of Plant and Environment*. 10(4), 73-83.

Submitted: 14/10/2024 **Accepted:** 10/01/2025 **Published:** 20/01/2025



OPEN

Responses of birds and mammals to long-established wind farms in India

Honnnavalli N. Kumara^{1✉}, S. Babu^{1✉}, G. Babu Rao^{1,2}, Santanu Mahato^{1,3},
Malyasri Bhattacharya^{1,4}, Nitin Venkatesh Ranga Rao¹, D. Tamiliniyan¹, Harif Parengal^{1,5},
D. Deepak¹, Athira Balakrishnan^{1,6} & Mahesh Bilaskar^{1,7}

Wind turbines have been recognised as an alternative and clean-energy source with a low environmental impact. The selection of sites for wind-farm often creates serious conservation concerns on biodiversity. Wind turbines have become a serious threat to migratory birds as they collide with the turbine blades in some regions across the globe, while the impact on terrestrial mammals is relatively less explored. In this context, we assessed the responses of birds and mammals to the wind turbines in central Karnataka, India from January 2016 to May 2018 using carcass searches to quantify animal collisions (i.e., birds and bats), fixed radius point count for bird population parameters, and an occupancy framework for assessing the factor that determines the spatial occurrence of terrestrial mammals. The mean annual animal fatality rate per wind turbine was 0.26/year. Species richness, abundance, and unique species of birds were relatively higher in control sites over wind turbine sites. Species and functional compositions of birds in control sites were different from wind turbine sites, explaining the varied patterns of bird assemblages of different feeding guilds. Blackbuck, Chinkara, Golden Jackal, and Jungle Cat were less likely to occupy sites with a high number of wind turbines. The study indicates that certain bird and mammal species avoided wind turbine-dominated sites, affecting their distribution pattern. This is of concern to the management of the forested areas with wind turbines. We raised conservation issues and mitigating measures to overcome the negative effects of wind turbines on animals.

The use and demand for energy have led to a high augmentation of non-renewable energy sources like oil, natural gas, coal, and hydrocarbons which attracted global attention due to their negative impact on terrestrial ecosystems and wildlife^{1–5}. The potential negative impact of energy development can result in habitat loss and fragmentation. Meanwhile, energy sources such as hydropower, wind, and solar energy, are being considered as alternative and clean energy sources to meet the growing demand for energy in the constraint of conventional energy sources^{6–9}. Developing hydropower, wind, and solar energy is encouraged as dams, turbines, and solar panels require no fossil raw materials, and it is also believed that it does not pollute the environment^{2,8}.

The process of tapping conventional energy sources such as hydropower, wind farms, and solar energy, has a number of severe environmental consequences. The conversion of the land to hydropower development alters hydrology dynamics, water quality, and greenhouse gas emissions¹⁰. Wind resources have a lower environmental impact when compared to hydel projects^{11–16} of generating the electricity from water, however, they have been shown to be harmful to wildlife due to mortality of bats and birds due to collisions with wind turbines^{17–22}. The fatality of animals was expected to be higher if the area chosen for the wind farm is rich in wildlife or falls in the migratory path of birds²³. The fatalities due to direct collision with the rotor blades of a wind turbine, the displacement or avoidance of animals due to the construction process and the noise generated by the wind turbines, the persistence of disturbance, and habitat loss caused by the construction of wind farms and their associated infrastructure are all considered to have a negative impact on wildlife²³.

¹Sâlim Ali Centre for Ornithology and Natural History, Anaikatty, Coimbatore, Tamil Nadu 641108, India. ²Manipal Academy of Higher Education, Madhav Nagar, Manipal, Karnataka 576104, India. ³Biopsychology Laboratory, Institution of Excellence, University of Mysore, Mysuru, Karnataka 570006, India. ⁴Wildlife Institute of India, Chandrabani, Dehradun, Uttarakhand 248001, India. ⁵Bharathiar University, Coimbatore, Tamil Nadu, India. ⁶National Institute of Advanced Studies, Indian Institute of Science Campus, Bangalore, Karnataka 560012, India. ⁷Department of Environmental Sciences, Savitribai Phule Pune University, Ganeshkhind Road, Pune 411007, Maharashtra, India. ✉email: honnavallik@gmail.com; sanbabs@gmail.com