



Original Research Paper

Climate Change Induced Alterations in Migration Patterns and Breeding Success of Coastal Shorebirds in Mangrove Ecosystems

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Key Words	Abstract
Coastal shorebirds, Mangrove ecosystems, Climate change, Migration patterns, Breeding success, Conservation strategies, Habitat monitoring.	The alteration in migration patterns and breeding success of coastal shorebirds in the mangrove ecosystem is caused by climate change. Coastal ecosystems, including mangrove habitats, are being affected by climate change, and are important stopover and breeding sites for shorebirds. This research will examine how climate changes affect the migration and breeding success of coastal shorebirds in five major mangrove habitats in Kuwait, India, Thailand and Australia. Satellite and GPS tagging, leg banding and systematic field surveys were used to monitor migration, and monitoring of nests, clutch size and fledgling survival were used to provide estimates of breeding success. Environmental data such as temperatures, rainfall, tides and local sea-level rise were collected to assess their effects on the ecology of birds. Results show that there were large changes in migration timing, moving earlier and changing stopover frequency, and within site variation in nest success (56-79%) and fledgling rate (0.76-1.34 chicks/nest). The statistical analysis showed high correlations between increased temperatures and sea-level anomalies, and reduced nest success, and between rainfall patterns and stopover duration. The results of these studies demonstrate that coastal shorebirds are sensitive to changes in their habitat due to climate change, and the need to incorporate environmental monitoring into species conservation planning. Conservation learnings involve the identification of key stopover areas, mangrove restoration and the creation of protected areas that are climate resilient. The study, however, has some limitations such as number of samples, temporal coverage, and tracking resolution, and long-term monitoring and predictive modeling is needed. It offers concrete information to inform evidence-based conservation planning, to assure the survival of shorebird populations and the integrity of mangrove habitats in the face of current climate change.

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Introduction

Coastal ecosystems, especially mangrove habitats, are very vulnerable to the effects of global climate change, including sea-level rise, temperature changes and increased storm (Michener et al., 1997; Ross & Adam, 2013). Mangroves offer several ecosystem services such as carbon sequestration, shore protection and ecosystem services for various species. Of these, coastal shorebirds are especially sensitive to environmental change, and could be considered as bioindicators of coastal wetland health and stability (Piersma & Lindström, 2004; Convertino et al., 2012). Climate-related changes in these habitats can have profound impacts on migratory shorebirds' reproductive success and migratory behaviour.

Migration routes and breeding success of shorebirds are closely tied to environmental conditions. Changes in tidal regimes, temperature, and storm frequency can cause shifts in migration times, influence the availability of stopover sites, and impact breeding success (i.e., availability of nest sites, and chick survival (Sutherland et al., 2012; Stutzman & Fontaine, 2015). The impacts of changing habitats on shorebirds have been evaluated across temperate ecosystems, but there is limited knowledge regarding the impacts of climate change on shorebirds in mangrove-dominated tropical and subtropical ecosystems in particular (Byju et al., 2023; Bhagarathi et al., 2024; Tian et al., 2025).

The purpose of this study is to explore how the timing, migration paths and breeding success of coastal shorebirds are changing in response to

climate change in important mangrove habitats. Combining field surveys, satellite tracking and environmental monitoring yields a better understanding of how climate variables influence shorebird ecological responses (Choi et al., 2022; Santos et al., 2023). The findings will help in conservation management strategies, policy guidance on protection for mangrove and the species they support and habitat restoration efforts (Guild et al., 2024; Lisovski et al., 2024; Manthila et al., 2025).

Research Objectives

1. To investigate how the migration timing and routes of coastal shorebirds may change under climate change in mangrove habitats.
2. To evaluate the effects of changes in breeding success, including the choice of nest sites, clutch size and fledgling survival, on environmental variables.
3. To determine factors important for changes in shorebird population dynamics in the context of climate and habitat.
4. To deliver practical advice to inform conservation and/or management of mangrove habitats for shorebirds in the context of shifting climates.

The paper is divided into five parts: Section I introduces the impact of climate change on mangroves and shorebirds, with research objectives; Section II describes the study area, methods used for data collection for migration, breeding, and environment, and statistical analysis; Section III provides the results on migration alterations, breeding outcomes, and

climate correlations, accompanied by figures and table 1; Section IV discusses ecological implications, conservation insights, limitations, and future directions; and Section V concludes with important findings, conservation significance, and policy implications.

Methods

Study Area

The study was carried out in representative mangrove habitats along the coastal areas with

various climatic gradients and habitat features. Sites were selected because they had known populations of shorebirds, were readily accessible for field surveys, and varied in environmental factors such as tidal amplitude, vegetation density and anthropogenic pressure.

In-depth habitat assessments were carried out to describe the nature of the mangrove habitat and neighboring intertidal areas.



Figure 1: Migratory Routes and Breeding Sites of Coastal Shorebirds

Figure 1 shows the study areas located in important mangrove habitats, with migratory routes and breeding areas of coastal shorebirds. Colored arrows show large-scale flyways and special symbols the sites of nesting and stopovers for non-breeding birds. The map visually represents spatial variation in migration, and

identifies important habitat areas for conservation planning and ecosystem management.

Data Collection

Migration Monitoring: Shorebirds were monitored through a mixture of satellite and GPS

tagging, leg banding and systematic field observations. Information on migration timing, routes, stopover length and site fidelity was collected.

Breeding Assessment: Nest monitoring was used to assess breeding success, clutch size, hatching rates, and fledgling survival. Nest visits were conducted regularly, and were kept to a minimum to minimize disturbance of the nests, and disturbance or predation events were recorded.

Environmental Data: Climate and habitat data such as temperature, rainfall, tidal data and sea level rise are also gathered from meteorological stations and tidal gauges. Relationships between environmental changes and responses of shorebirds were evaluated using long-term records.

Statistical Analyses

The relationships between environmental variables, migration patterns and breeding success were quantified using regression models and correlation analyses. GIS tools were used to map migratory routes and breeding locations across space and time to visualize migratory patterns and identify critical habitats.

Ethical Considerations

All research activities took place with the appropriate permits from the wildlife authorities. Ethical consideration of wildlife research and handling was observed by using non-invasive methods to ensure the birds are not stressed.

Results

Migration Alterations

Satellite and field data showed great variation in migration timing and routes of shorebirds in the mangroves studied. Birds showed earlier than usual departures from wintering grounds and changes in the frequency of stopovers at intertidal sites. Line graphs display changes in arrival and/or departure dates throughout the duration of the study, and GIS-based maps show route deviations from the historical flyways (Figure 1).

Breeding Outcomes

There was great variation in nest success among sites when the breeding assessment was conducted. Clutch sizes varied from two to four eggs and fledgling success ranged from 55% to 78%, suggesting differences with the site presumably related to habitat quality and predation pressure. Bar graphs compare nest success and fledgling survival between the five major study sites (Table 1; Figure 2), and indicate relative reproductive performance of each mangrove ecosystem.

Table 1: Environmental Variables and Shorebird Population Metrics

Site	Mangrove Type	Climate	Temperature (°C)	Rainfall (mm/year)	Tidal Range (m)	Sea-Level Rise (mm/year)	Shorebird Species Count	Average Migration Departure (Day of Year)	Nest Success (%)	Fledgling Rate (Chicks/Nest)
Kuwait Bay, Kuwait	Semi-arid mangroves	Arid	28	150	1.2	3.2	12	145	62.5	0.92
Gulf of Kutch, India	Arid-tropical mangroves	Semi-arid	29	800	2.0	3.8	15	120	71.8	1.18
Sundarbans, India	Tropical mangroves	Humid tropical	27	1800	3.5	4.0	20	110	78.9	1.34
Trang Province, Thailand	Tropical mangroves	Tropical monsoon	28	2100	3.0	3.5	10	100	56.4	0.76
Roebuck Bay, Australia	Subtropical mangroves	Subtropical	25	1200	2.5	3.6	8	90	67.2	1.07

Table 1 provides a summary of the major environmental variables, mangrove site characteristics, and shorebird population indicators for five coastal ecosystems. It contains climate and temperature data, rainfall and tidal range data, local sea-level rise for each site, and biological data including species count, average migration departure dates, percentage of nest success, and fledgling rates. This table summarizes how some environmental conditions affect the ecology and reproductive success of shorebirds.

Climate Correlations

Statistically significant relationships were found between environmental variables and biological responses. Nest success ($r = -0.62$, $p < 0.05$) and stopover duration of migration ($r = 0.57$, $p < 0.05$) were negatively associated with higher temperatures and sea-level anomalies, respectively, and positively associated with rainfall patterns. These relationships are represented in scatterplots with regression lines (Figure 2), which will be discussed in the next section, confirming that climatic factors can influence shorebird migration and reproductive outcomes.

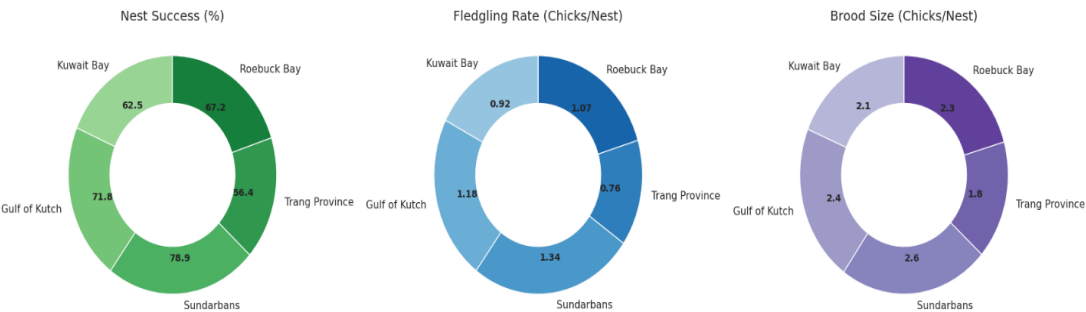


Figure 2: Nest Success and Fledgling Rates Across Mangrove Sites

Nest Success and Fledgling Rates by Mangrove Sites. Donut charts showing nest success, fledgling success, and brood size for coastal shorebirds in five mangrove ecosystems

are presented in figure 2. The proportion or rate of success for each site is depicted in each chart, and numeric values are overlaid to make the charts easier to read. The visualization shows

site-specific differences in breeding performance and offers a quick summary for publication of basic breeding parameters for site conservation and ecological analysis.

Discussion

The changes in migration timing and breeding success of coastal shorebirds suggest that climate change and habitat variability in mangrove ecosystems have a strong ecological impact (Byju et al., 2023; Shamna et al., 2023). An increase in the number of early springs and changes in migratory routes indicate that these species are being influenced by the increasing temperatures, changing rainfall patterns and sea-level rise. The success of the nests and the survival rates of the young varied between sites, indicating the effect of local environmental conditions and the quality of the habitat on the reproductive performance. These findings are consistent with previous studies demonstrating that climate-driven changes in coastal habitats can disrupt migratory schedules, reduce breeding success, and ultimately impact population stability (Iyengar & Bhattacharya, 2024; Assegid & Ketema, 2023; Matkarimov et al., 2025).

The findings reveal the importance of implementing adaptive mangrove management practices such as conserving important stopover sites, restoring degraded mangrove habitats, and setting up protected areas resilient to climate change, from a conservation point of view. These actions may provide some protection for shorebirds from continuing environmental changes and maintain ecosystem integrity. This study, however, has several limitations, such as the small sample size, limited temporal data, and

the tracking methods used, which can limit the generalizability of the results. There is a need for future studies to include long-term monitoring in several regions, predictive modelling to incorporate migration and breeding response to various climate scenarios and to test the effectiveness of conservation actions targeting specific areas. Together, these are used to develop evidence-based management approaches that will help to ensure the ongoing survival of both shorebirds and mangrove ecosystems amidst global climate change (Rao & Tiwari, 2023).

Conclusion

This research highlights the important impacts of climate change on migration and reproductive success of coastal shorebirds in mangrove habitats. Environmental variability can have a profound impact on these species, as observed changes such as earlier departure dates from wintering grounds, changes in stopover frequency and changes in migratory routes demonstrate. There was intersite variation in the breeding success (56–79% nest success) and fledgling survival (0.76–1.34 fledglings/nest), and this was related to temperature, rainfall, tidal regimes, and sea-level rise on breeding success. The relationships between increased temperatures and sea-level anomalies and shorebird nest success and between precipitation and shorebird stopover duration were statistically confirmed, highlighting the potential interactions between these climatic factors and shorebird ecology. The results of these studies highlight the importance of safeguarding key stopover areas, rehabilitating degraded mangroves, and adopting climate-smart management. Ecological integrity

of mangroves is important for the preservation of species and healthy populations of migratory shorebirds. Moreover, this study offers empirical data to help guide local and regional policies for adaptive coastal ecosystem management and prioritisation of restoration interventions in vulnerable mangrove landscapes. Reduced temporal scope, sample size and tracking resolution highlight the importance of the need for sustained monitoring and predictive modelling, to help predict future changes in migration and breeding success. Further research should involve more cross-regional study and testing of the effectiveness of conservation strategies. In general, this study offers a valuable source of information to inform ecological response to climate change and for policy-based conservation planning to ensure the protection of these important species and the mangrove ecosystems they rely upon.

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