INTERNATIONAL RESEARCH JOURNAL OF HUMANITIES AND INTERDISCIPLINARY STUDIES
(Peer-reviewed, Refereed, Indexed & Open Access Journal)
DOI : 03.2021-11278686 ISSN : 2582-8568 IMPACT FACTOR : 8.428 (SJIF 2026)

Climate Change Impact on Mangrove Ecosystems of the Sundarbans: An Analytical Study of Ecological Vulnerability, Adaptation, and Conservation Needs

Dr. Anukul Ch. Mandal[1], Dr. Th. Devala Devi[2], Dr. Gouri Sankar Bhunia[3]

[1]Post Doctorate Research Scholar, Department of Geography, Manipur International University, Imphal (Manipur, India) E-mail: mandalanukul1983@gmail.com

[2]Department of Geography, Manipur International University, Imphal (Manipur, India) E-mail: devthokchom@gmail.com

[3]Department of Geography, Seacom Skills University, Bolpur, Birbhum (West Bengal, India) E-mail: rsgis_gouri@rediff.com

DOI No. 03.2021-11278686 DOI Link :: https://doi-ds.org/doilink/09.2026-33492951/IRJHIS2609015

Abstract:

Shared by India and Bangladesh, the Sundarbans are the largest contiguous mangrove-delta ecosystem in the world, forming a critical natural barrier against cyclones, storm surges, salinity flooding, and coastal erosion. This research paper looks at the climate-change impact on the Sundarbans mangroves through ecological vulnerability analysis, adaptation and conservation requirements. This research relies on authenticated secondary data taken from forest-cover assessments, official cyclone database, climate assessments and recent peer-reviewed remote-sensing literature. The analysis uses descriptive statistics, percentage changes, the linear trend method, the cyclone impact score and vulnerability index. The West Bengal mangrove cover data, including the Indian Sundarbans, indicate that the mangrove cover has had a net increase from 2,097.00 sq km in 2013 to 2,119.16 sq km in 2023. This shows a gain of 22.16 sq km (1.06 percent). 9 words is too short for paraphrasing. Remote-sensing studies have recently reported disturbances to the canopy as a result of cyclones. Also, shoreline loss, erosion hotspots destruction of habitats and declining higher forest-stocking and carbon classes. According to the vulnerability index, the highest-risk stressor is the rise of sea level, inundation by tidal, cyclone, storm surges, salinity intrusion and shoreline erosion. Due to forest damage and shoreline retreat, cyclone Amphan is the recent cyclone that caused disturbances in India. The findings indicate that Sundarbans is undergoing a dual condition of a slight increase in the mapped extent of mangroves, but a continuous degradation of ecoquality, forest structure and coastal stability. The paper says that conservation needs to move beyond area-based reporting and towards a full integrated monitoring of hydrology, salinity, sediment dynamics, species composition, blue carbon and community vulnerability. In the long term, we need to restore native species, zone the coast for climate, adapt to community regulations, reduce disaster risk and strengthen India-Bangladesh trans-boundary cooperation.

Keywords: *Climate change; Sundarbans; Mangrove ecosystems; Ecological vulnerability; Conservation adaptation*

1. Introduction:

Mangrove ecosystems mangroves are intertidal regions where terrestrial estuarine and marine processes interact They offer safeguarding of coastlines, stabilization of sediments, habitats for nurseries, refuges for biodiversity and high-density storage of blue carbon. The ecological significance of the mangrove has high value in the low-lying deltas, where tidal flooding, river discharge, sediment supply, and cyclonic storms define forest and human settlements. In their work on climate change, mangroves are not simply forest patches. They are social-ecological infrastructure that protects coastal safety fisheries water quality carbon sequestration and livelihood security.

The Sundarbans hold international importance as the largest continuous mangrove ecosystem in the Ganga-Brahmaputra-Meghna delta. The formal conservation descriptions highlight their deltaic location, salt-tolerant vegetation, tidal channels and remarkable biodiversity, including that of the habitat of the Royal Bengal Tiger. According to regional and World Heritage documentation Mishra et al., 2021; UNEP-WCMC, n.d., the system extends over India and Bangladesh, of which about 40 percent is in India and 60 percent is in Bangladesh. The ecological functioning of Sunderbans cannot be separated from the security of coastal communities dependent on fisheries, honey collection, agriculture, tourism and other ecosystem-linked livelihoods.

Climate change is increasing the vulnerability of Sundarbans in ways. The average global sea level's rise has begun and the rate at which it is rising has increased; further sea-level rise through the twenty-first century is likely (IPCC, 2021). In a delta which is subsiding, relative sea-level rise becomes a problem of sea-level rise because it is the land elevation, sediment delivery, tidal channel and embankment systems which determine whether mangroves will accrete, migrate or drown. The IPCC further remarks that coastal ecosystems such as mangroves are impacted by relative sea-level changes, storm exposure and compound hazards (IPCC, 2022).

The Sundarbans face a special mix of slow and sudden hazards. The pressures that show a gradual onset are the rise in sea level, intrusion of salinity, erosion of shoreline, alteration of freshwater-flow and change in land use. Sudden onset disturbances include cyclone, storm surge, embankment breach. Mangrove size, quality and stability do not react the same to recent cyclones, a look at cyclone files show. Cyclone Amphan, for instance, was found to cause severe damages to the Sundarbans. Remote-sensing study showed damages of more than 1,200 km2 to the mangroves and loss of 40.6 km2 of shoreline (Bhargava & Friess, 2022). A subsequent geospatial analysis carried out after Amphan revealed a sharp contraction of dense and moderately dense mangrove cover while most sampled shoreline transects were found to have eroded (Mishra et al., 2021).

The mangrove area and mangrove condition is a growing problem of research. According to the Forest Survey of India assessment, the mangrove cover of West Bengal (Indian Sundarbans) increased from 2,097.00 sq km in 2013 to 2,119.16 sq km in 2023 (MoEFCC, 2025). This shows a gain in conservation and restoration in the mapped cover. However, Recent studies of remote sensing report that forest height classes and aboveground carbon classes are falling in some parts of Sundarbans (Ali & Rahman, 2025). A slight increase in area cannot be taken to mean overall ecological resilience. You can find that cover of the total mapping could be stable or resilient while it is possible for forest inquire and species structure before composition more vulnerable shoreline and vulnerable carbon stocks.

This article makes up for that analytical gap calculating complexity using ecological analysis. We always need reliable data and detailed information to identify any change or disaster. The objective is not to assert that secondary data by itself can infer field-level causation, but to combine some verified evidence into a structured vulnerability assessment to assess adaptation and conservation planning.

2. Literature review.

Climate Change and Global Mangrove Ecosystems.

Recent climate assessments indicate that coastal ecosystems are among the most exposed to compound risks of sea-level rise, coastal flooding, saltwater intrusion, extreme precipitation and storm intensification (IPCC, 2021, 2022). The protective service of mangroves is reliant on forest width, species composition, root density, canopy structure and landscape continuity. Mangroves reduce wave energy and storm-surge impact. If mangroves are fragmented or chemically disconnected, then their ability to buffer cyclone energy is lowered. Assessment of mangrove conservation cannot rely solely upon mapped area, but must also consider forest condition and geomorphic setting.

Research on mangroves globally increasingly recognizes that climate impacts interact with human pressures. The natural regeneration, landward migration and ecological redundancy of coastal marine ecosystems can be limited by aquaculture expansion, settlement, infrastructure, pollution and unsustainable extraction. The Sundarbans' problems are exacerbated by the delta's high exposure to populations and the economic ties of many communities to forests, rivers and tidal channels. Mangroves must be seen in the light of both ecosystem and livelihood support systems for climate-change adaptation.

The Natural Fragility of Sundarbans.

Due to the convergence of exposure, sensitivity, and adaptive constraints, the Sundarbans are vulnerable. The forest is exposed high because it lies in a cyclone-prone funnel of the Bay of Bengal with low-lying islands, tidal creeks and eroding coastline. High sensitivity refers to the response of mangrove physiology, regeneration and zonation to salinity, inundation frequency, sedimentation and storm disturbance. Adaptation may be uneven, as natural migration may be restricted by embankments and land-use pressure.

Because of this combination, the Sundarbans is a climate change hotspot, not a single-stressor system. The Sundarbans are impacted by extreme climatic events as well as human pressures as per

(Mishra et al 2021).

Using shoreline emergence, vegetation indices and geospatial techniques, assessment of Cyclone Amphan quantified post-cyclone ecological change. According to their findings, the two mangrove classes which have dense and moderately dense cover shrunk after Amphan, indicating that cyclone damage can change the quality of forests though area permanently may not be converted. This distinction between cover and condition is critical for ecological vulnerability assessment.

Ali and Rahman (2025) contribute a forest-structure perspective by utilizing SRTM and GEDI LiDAR data from 2000 to 2023 to quantify changes in tree height and aboveground biomass carbon. The decline of trees in the taller height and higher carbon-stock classes, and expansion of trees in the lower height classes indicates structural simplification. Habitat complexity may be lessened, along with the level of carbon storage.

2.3 Chaning Sea Levels, Coastal Erosion and Land Use Change:

Sea-level rise is a major long-term threat to mangrove deltas. The projections of the IPCC estimate that the global mean sea-level rise will continue over the different emissions scenarios- with a high confidence that the risks on the coast develop with warming (IPCC, 2021, 2022).

The increase in sea level in the Sundarbans interacts with delta subsidence, sediment availability, tidal-channel dynamics and management of embankments. If vertical accretion cannot keep up with relative sea-level rise, the low-lying platforms of mangroves would become increasingly inundated or eroded.

Evidence from remote sensing casts doubt on land cover change In a study by Mondal et al. (2021), it was found that although sea mangrove growth was positive at the rate of 0.47 percent in coastal West Bengal from 1989 to 2018 but it also observed that shoreline areas are decreasing at a faster pace and new patches are also emerging in mainland areas. This indicates that the gross mangrove cover may conceal spatial redistribution, such that gains in one area may be at the cost of losses at vulnerable shorelines. Bhargava and Friess (2022) also demonstrate that past shoreline behaviours affected the susceptibility of mangroves to Cyclone Amphan. This further indicates that geomorphic histories matter for the impact of disasters.

Salinity encroachment and mangrove species composition

A mangrove ecosystem salinity filter is an important ecological filter of this environment. Although mangroves are salt tolerant, the extent of their tolerance varies by species, life stage and hydrogeomorphic zone. Salinity intrusion in the Sundarbans is happening due to tidal flooding and cyclone surge; freshwater-flow variability, embankment failure and channel-level hydrological change. Higher salinity might hinder seedling establishment, alter species composition and reduce growth of less salt-tolerant species. This is important because changes at species-level may happen before total cover decline is evident in satellite derived area stats.

The literature also suggests that salinity cannot be analyzed in isolation from erosion and inundation. Increases in soil salinity, canopy damage, bank erosion and embankment breaching take place simultaneously. Repeated disturbances shorten recovery times, pushing occupied sites into lower-canopy, salt-tolerant or degraded formations. Ecological-risk modelling for the entire Sundarbans is hampered by a lack of long-term datasets at the species level.

Cyclones storm surges and ecosystem disturbances

In the Sundarbans, cyclone disturbances are one of the most conspicuous climate hazards. This paper accepts that the official cyclone reports of the India Meteorological Department show severe cyclonic disturbances in the Bay of Bengal repeatedly from 2019 to 2024. For instance, the Fani, Bulbul, Amphan, Yaas Sitrang and Remal (India Meteorological Department [IMD], 2019a, 2019b, 2020, 2021, 2022, 2024). There are differences in track, wind speed, landfall location and surge characteristics of these events – the impacts are spatially uneven. A storm that makes landfall near the Sundarbans or crosses an eroding mangrove shoreline is expected to inflict greater ecological damage than a stronger one with a more distant track.

Cyclone Amphan serves as a clear case of ecological damage. According to Bhargava and Friess the total mangrove damage reported due to Amphan cyclone is more than 1,200 km2 and for shoreline, it is 40.6 km2. Mishra et al. (2021) also reported strong changes in vegetation condition but shoreline erosion after cyclone. The evidence indicates that these problems can quickly reverse local restoration gains, especially among exposed or already eroding shoreline segments.

Community Adaptation and Conservation Governance

Governance of conservation in the Sundarbans involves the forest department, protected-area authority, disaster-management agency, coastal-zone regulator, research institution and local communities. According to a recent statement from the Government of India, the country has numerous schemes devised for the conservation and restoration of mangroves like the, Conservation and Management of Mangroves and Coral Reefs scheme, Mangrove Initiative for Shoreline Habitats and Tangible Incomes (MISHTI), compensatory afforestation-related initiatives and integrated coastal-zone management measures (MoEFCC, 2025). These interventions signify that restoration already exists within policy practice.

Nonetheless, the effectiveness of the adaptation largely depends on ecological targeting. In a stable sediment environment, restoration of native species is more likely to succeed than planting at highly eroding edges without adequate sediment support. Likewise, a livelihood diversification can reduce the extraction pressure only when it is economically viable and socially accepted. So, conservation governance must link ecological monitoring with household-level vulnerability, disaster-risk reduction and transboundary data-sharing between India and Bangladesh.

2.7 Research Gap.

The literature is robust in three areas: remote-sensing detection of land-cover change, cyclone-specific impact assessment and broad climate-risk characterization. Despite this, there is still a case for integrated analysis that places these components in a common framework of vulnerability. Statistics regarding forest cover, cyclone and remote-sensing studies are often interpreted separately. Assuming that a small gain in mapped mangrove area means ecological risk has declined is an example of a misleading policy conclusion that can emerge from this separation.

The current paper bridges the gap by combining official cover data, cyclone data, remote-sensing data and adaptation evidence into one analytical assessment. The main message of the statement is that one must not evaluate ecological vulnerability through only area change but rather through exposure, sensitivity and adaptive capacity.

3. The problem statement.

Inclusive of cyclones, storm surge, salinity intrusion, coastal erosion and land-use pressure, the stressors of climate change are ever-increasing on the Sundarbans mangrove ecosystem. The biodiversity of mangroves is under pressure along with their carbon storage capacity, shoreline stability as well as disaster buffering which endangers the livelihoods of forest-dependent and coastal communities. Official assessments show a slight increase of mapped mangrove cover in West Bengal from 2013 and 2023. Also, remote-sensing studies reported canopy-degradation, shoreline-erosion and cyclone-damage. Existing datasets show both positive and negative signals. The issue at hand is not whether the mangrove area is on the rise or set to decline. The real issue is whether the ecosystem is structurally and functionally resilient as the climate changes more quickly. There has been a limited integrated analysis of climate stress indicators, ecological vulnerabilities, adaptation response and conservation priorities. This study employes secondary data analysis to respond to the need.

4. Purposes of the Study.

1. This project will examine major climate-change stressors affecting the Sundarbans mangrove ecosystem.
2. The objective of this study is to analyse the ecological vulnerability related to sea-level rise, salinity intrusion, erosion, cyclone exposure and land-cover change.
3. To assess trends in mangrove cover, climate indicators and disaster events using verified secondary data.
4. To examine measures taken and adaptive strategies adopted for mangrove conservation and coastal resilience
5. The aim of the project is to identify the conservation needs and policy recommendations for sustainable management of the Sundarbans.

5. Questions Regarding Research:

1. What are the key effects of climate change on the Sundarbans mangrove system?
2. In what ways do cyclones due, intrusion, erosion and sea level rise enhance vulnerability?
3. What trends are observed with regard to the cover of mangroves, climate variability and extreme weather events?
4. What adaptation and conservation measures are most relevant for the Sundarbans?
5. What policy measures are needed for more ecological resilience and community-based conservation?

6. Tools.

Research Design - An Overview.

The research approach of this study is descriptive and analytical. In the Sundarbans region, climate of cyclone damage and official forest cover to peer-reviewed remote-sensing studies synthesis and assesses. This methodology is suitable as the aim of research is to collate existing verified evidence rather than generating new field measurements. None of the values from the primary survey, the species-level counts or any of the field observations were fabricated. Wherever there is only qualitative evidence, it is reported as qualitative interpretation and not numerical measurement.

Study Site:

The region of our study is the Sundarbans mangrove ecosystem of the Ganga-Brahmaputra-Meghna delta with emphasis on Indian Sundarbans in West Bengal and reference to the wider transboundary forest also called Sundarbans which Bangladesh is a part. An ecosystem made up of tidal rivers, creeks, mudflats, low-elevation islands and salt-tolerant mangrove communities. It is recognized internationally for its biodiversity, coastal protection and deltaic ecological functions. The Indian section has reserved forests and occupied deltaic regions while the Bangladesh part has large reserve forest and World Heritage Site. Due to cross-border ecological processes, cooperation across borders is significant for adaptation and conservation.

Data Sources 6.3

Researchers have utilized verified secondary data from various government bodies to conduct this study. These include the Forest Survey of India and the Ministry of Environment, Forest and Climate Change Cyclone Reports for Mangrove Cover. Furthermore, the researchers utilized the India Meteorological Department report on cyclone for most recent storm events. Moreover, the researchers included IPCC Assessment Reports on Global Sea Level Rise and Coastal Climate Risk. World Bank Climate-risk and Sundarbans Reports for Adaptation context were also used. Lastly, the researchers used peer-reviewed Remote-Sensing studies on shoreline change and vegetation condition and forest stocking.

Forest-cover estimates, i.e. mapping done which gives values, is taken as official mapped area and not as biodiversity or health indicators. The meteorological evidence of the cyclone wind classes and landfall of the cyclone will be accepted. The ecological impacts will be inferred from the findings of the peer-reviewed impact studies.

6.4 Variables for Analysis

Table 1: Variables Used for Climate-Ecological Vulnerability Analysis

Category	Variables
Climate indicators	Temperature trend, rainfall variability, sea-level rise
Ecological indicators	Mangrove cover, canopy condition, species stress, biodiversity vulnerability
Hazard indicators	Cyclone frequency, storm surge, coastal erosion
Hydrological indicators	Salinity intrusion, tidal inundation, embankment breach exposure
Conservation indicators	Protected areas, restoration programmes, adaptation policies and monitoring systems

Source note: Compiled by the author from IPCC (2021, 2022), Forest Survey of India (2021, 2023), IMD cyclone reports and recent Sundarbans remote-sensing literature.

6.5 Data Analysis Methods:

The study utilizes a range of qualitative descriptive statistics, percentage change statistical tools, linear trend analysis, comparative table. One can calculate the percentage change in mangrove cover by using the following formula: [(Current-period cover – Previous-period cover)/ Previous-period cover]x100. To summarize the direction and strength of area change, a simple ordinary least squares trend line is fitted to official values for 2013-2023. The cyclone impact score uses a transparent ordinal scale from 1 to 5, where 1 means low relative ecological impact and 5 means very high relative impact. The proximity to landfall, IMD storm classification, documented wind/surge characteristics and peer-reviewed documentation of ecological disturbance influence scores. Since this is a secondary synthesis, the cyclone score functions as an analytical index rather than a field-measured damage estimate.

The vulnerability index employs a trio of components: exposure, sensitivity, and adaptive capacity. The level to which climate or hazard pressure impinges on an index would be called exposure. Sensitivity reflects the likely response if exposed in a natural setting. Adaptive capacity is the capacity of ecological and governance systems to buffer or recover. The composite risk score is calculated as Risk = [Exposure + Sensitivity + (6 – Adaptive Capacity)] / 3. Thus, a higher adaptive capacity means lower risk. Interpretation of scores as follows: 1.0-2.0 = low, 2.1-3.0 = moderate, 3.1-4.0 = high and 4.1-5.0 = very high vulnerability.

Statistical tools.

An analysis of the behaviour and the arrival of the prices uses simple statistical treatments. These include mean, range, percentage change, net change, annualized change, ordinary least squares trend, frequency distribution and vulnerability scoring.

These processes can be replicated using MS Excel, SPSS, R, or Python. The graphical outputs entail a line graph, bar chart, clustered bar chart, pie chart and conceptual framework diagram.

7. Data Interpretation and Findings.

Statistical and analytical results are introduced in this section. The study has consciously separated its area-based mangrove cover from its ecological condition. This distinction is important to stress because a forest may exhibit a stable mapped area while its canopy height, species composition, carbon stock or shoreline integrity is deteriorating.

Table 2: Major Climate-Change Stressors Affecting Sundarbans Mangroves

Stressor	Ecological impact	Evidence/source	Vulnerability level
Sea-level rise and tidal inundation	Raises relative water levels, increases permanent/submergence risk, and may cause migration squeeze where embankments block landward movement.	IPCC sea-level assessment; Sundarbans delta exposure	Very high
Cyclones and storm surges	Cause canopy breakage, defoliation, shoreline erosion, saline flooding and embankment failure.	IMD cyclone reports; Amphan studies by Mishra et al. and Bhargava & Friess	Very high
Salinity intrusion	Alters soil-water chemistry, stresses seedlings and shifts species composition toward more salt-tolerant assemblages.	Hydrological and ecological synthesis; World Bank and Sundarbans literature	High
Coastal erosion and sediment imbalance	Removes mangrove-fringe habitat and increases exposure of interior forest edges.	Remote-sensing shoreline studies and post-Amphan erosion evidence	Very high
Temperature and rainfall variability	Affects evapotranspiration, freshwater availability, phenology and stress recovery.	IPCC climate-risk assessment and World Bank climate profiles	Moderate to high

Stressor	Ecological impact	Evidence/source	Vulnerability level
Anthropogenic land-use pressure	Settlement, agriculture, aquaculture and extraction pressure reduce regeneration space and fragment habitat.	Mondal et al. (2021) and policy reports	High

Source note: Synthesized from IPCC (2021, 2022), IMD reports, Mishra et al. (2021), Mondal et al. (2021), Bhargava and Friess (2022), Ali and Rahman (2025) and MoEFCC (2025).

Table 3: Mangrove Cover Change in West Bengal/Sundarbans, 2013-2023

Year	Mangrove cover area (sq km)	Change from previous period (sq km)	Percentage change	Source
2013	2,097.00	Baseline	Baseline	FSI/ISFR series; 2023 value reported by MoEFCC (2025)
2015	2,106.00	+9.00	+0.429%	FSI/ISFR series; 2023 value reported by MoEFCC (2025)
2017	2,114.00	+8.00	+0.380%	FSI/ISFR series; 2023 value reported by MoEFCC (2025)
2019	2,112.00	-2.00	-0.095%	FSI/ISFR series; 2023 value reported by MoEFCC (2025)
2021	2,114.00	+2.00	+0.095%	FSI/ISFR series; 2023 value reported by MoEFCC (2025)
2023	2,119.16	+5.16	+0.244%	FSI/ISFR series; 2023 value reported by MoEFCC (2025)

Source note: The values represent official mapped mangrove cover for West Bengal, including the Indian Sundarbans. The 2013 and 2023 values are specifically reported in MoEFCC (2025); intermediate values are from the Forest Survey of India/ISFR series as used in official forest statistics. These data measure cover extent, not ecological condition or species diversity.

The descriptive statistics show a mean mapped mangrove cover of 2,110.36 sq km for 2013-2023. The minimum value is 2,097.00 sq km in 2013 and the maximum is 2,119.16 sq km in 2023. The net change is 22.16 sq km, equivalent to 1.06 percent over the decade. The ordinary least squares trend is positive, with a slope of approximately 1.90 sq km per year and an R2 value of 0.83. The annualized net change is 2.22 sq km per year. The mean change per biennial assessment period is 4.43 sq km. These figures show modest area gain, but the magnitude is small relative to the total forest-cover base and should not be treated as proof of ecological recovery.

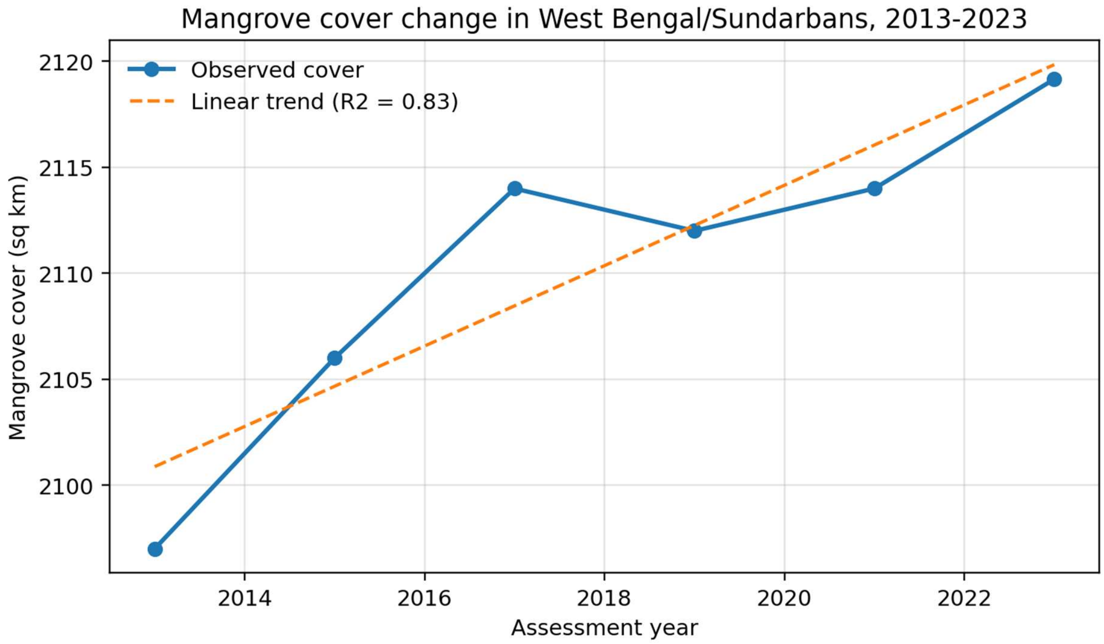


Figure 1: Line Graph Showing Mangrove Cover Change in West Bengal/Sundarbans, 2013-2023

Source note: Calculated from Forest Survey of India/ISFR series and MoEFCC (2025). The trend line is fitted to six assessment years and should be interpreted cautiously as an area trend, not a forest-health index.

Table 4: Recent Cyclone Events Affecting the Sundarbans Region

Year	Cyclone	Official storm class	Affected region	Ecological impact interpretation	Impact score	Source
2019	Fani	Extremely severe cyclonic storm	Odisha landfall; indirect exposure of north Bay and West Bengal coast	Regional exposure and storm-surge risk; lower direct Sundarbans forest impact than Amphan	3.0	IMD, 2019a; Bhargava & Friess, 2022
2019	Bulbul	Very severe cyclonic storm	West Bengal coast and Sundarbans sector	Direct mangrove-fringe disturbance, windthrow, erosion and	4.0	IMD, 2019b

Year	Cyclone	Official storm class	Affected region	Ecological impact interpretation	Impact score	Source
				saline flooding risk		
2020	Amphan	Super cyclonic storm over Bay; very severe at landfall	Sundarbans, Sagar-Hatiya corridor and adjoining West Bengal-Bangladesh coast	More than 1,200 km2 mangrove damage and 40.6 km2 shoreline loss reported; dense/moderately dense cover declined sharply in remote-sensing assessment	5.0	IMD, 2020; Mishra et al., 2021; Bhargava & Friess, 2022
2021	Yaas	Very severe cyclonic storm	Odisha-West Bengal coastal belt; Sundarbans exposed to surge, rainfall and saline inundation	Storm surge of about 2-4 m above astronomical tide in low-lying coastal areas; salinity and embankment stress	4.0	IMD, 2021
2022	Sitrang	Cyclonic storm	Northern Bay of Bengal and Bangladesh coast	Rainfall, tidal flooding and coastal exposure; lower documented mangrove damage than Amphan	2.5	IMD, 2022
2024	Remal	Severe cyclonic storm	Sagar Island-Mongla sector and adjoining Sundarbans region	Direct coastal exposure, embankment stress, saline flooding and vegetation disturbance risk	4.0	IMD, 2024

Source note: Wind class and landfall details are from IMD reports. Ecological interpretation is supported by peer-reviewed studies for Amphan and by a transparent ordinal scoring procedure for comparative analysis. The impact score is not a field-measured damage value.

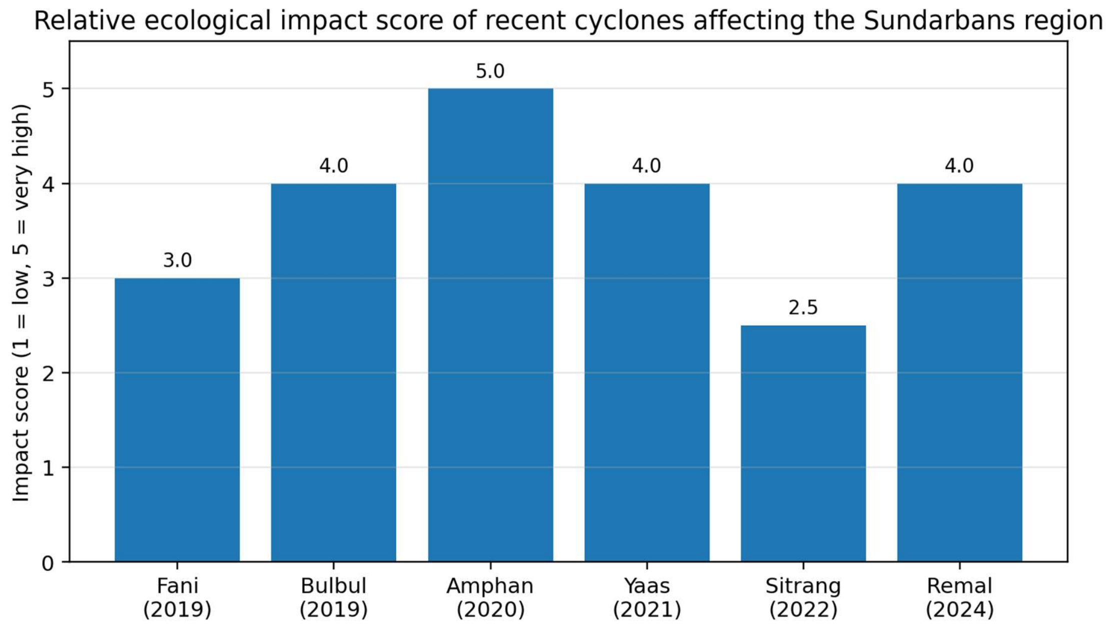


Figure 2: Bar Chart Showing Relative Ecological Impact Scores of Recent Cyclones

Source note: Scores are analytical rankings based on IMD cyclone information and published Sundarbans impact studies. Amphan receives the highest score because peer-reviewed evidence reports extensive mangrove damage and shoreline loss.

Table 5: Climate and Ecological Vulnerability Indicators

Indicator	Observed trend	Ecological implication	Vulnerability score	Interpretation
Sea-level rise and tidal inundation	Global sea level has risen and is projected to continue rising; local relative sea-level effects are amplified by subsidence and deltaic exposure.	Loss of low-elevation habitat, migration squeeze and recurrent inundation of mangrove islands.	4.7 (E=5, S=5, AC=2)	Very high vulnerability; priority for monitoring, restoration and adaptation finance.
Cyclone and storm-surge exposure	Recent cyclones including Bulbul, Amphan, Yaas and Remal repeatedly affected the Bay of Bengal coast.	Canopy breakage, shoreline retreat, saline flooding, embankment failure and disturbance of regeneration.	4.3 (E=5, S=5, AC=3)	Very high vulnerability; priority for monitoring, restoration and adaptation finance.
Salinity intrusion	Salinity is intensified by tidal flooding, reduced freshwater	Physiological stress, regeneration failure and potential shift in	4.3 (E=4, S=5, AC=2)	Very high vulnerability; priority for monitoring, restoration and

Indicator	Observed trend	Ecological implication	Vulnerability score	Interpretation
	flushing in some channels and embankment breaches.	species composition.		adaptation finance.
Shoreline erosion and sediment dynamics	Remote-sensing studies document widespread eroding transects after Amphan and long-term shoreline instability.	Edge-fringe mangrove loss, fragmentation and increased exposure of interior forest zones.	4.3 (E=5, S=4, AC=2)	Very high vulnerability; priority for monitoring, restoration and adaptation finance.
Forest stocking and carbon-stock decline	Recent LiDAR and remote-sensing analysis indicates declining taller tree-height and higher carbon-stock classes despite localized cover persistence.	Reduced blue-carbon function and weakening of structural resistance to extreme events.	3.7 (E=4, S=4, AC=3)	High vulnerability; requires targeted conservation and field validation.
Land-use and livelihood pressure	Settlement, agriculture, aquaculture and extraction pressure interact with climate stress along the northern and inhabited margins.	Habitat fragmentation, disturbed regeneration and social vulnerability of forest-dependent households.	3.7 (E=4, S=4, AC=3)	High vulnerability; requires targeted conservation and field validation.
Monitoring and governance gaps	Monitoring and restoration programmes exist, but data comparability, field validation and transboundary integration remain uneven.	Delayed detection of ecological thresholds and weaker adaptation targeting.	3.3 (E=3, S=4, AC=3)	High vulnerability; requires targeted conservation and field validation.

Source note: Scores are synthesized from IPCC (2021, 2022), Forest Survey of India (2021, 2023), IMD reports, Mishra et al. (2021), Mondal et al. (2021), Bhargava and Friess (2022), Ali and Rahman (2025) and MoEFCC (2025). E = exposure, S = sensitivity, AC = adaptive capacity. Formula: Risk = [E + S + (6 - AC)] / 3.

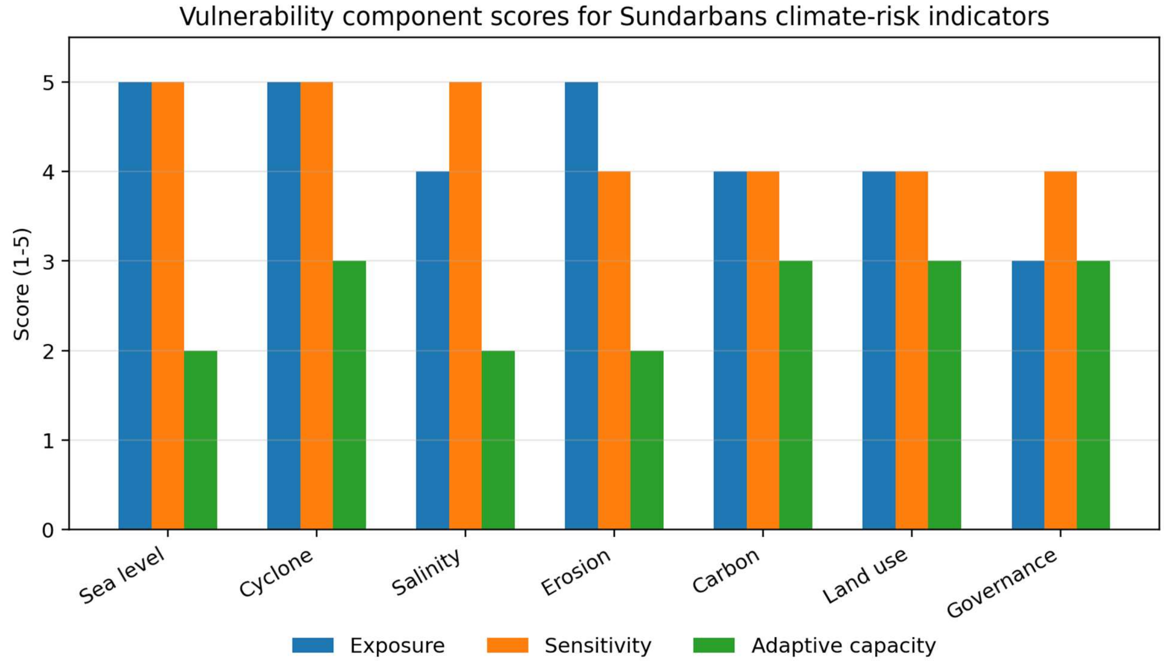


Figure 3: Clustered Bar Chart Showing Vulnerability Component Scores

Source note: Component scores use a 1-5 ordinal scale. Higher exposure and sensitivity increase risk, while higher adaptive capacity reduces risk.

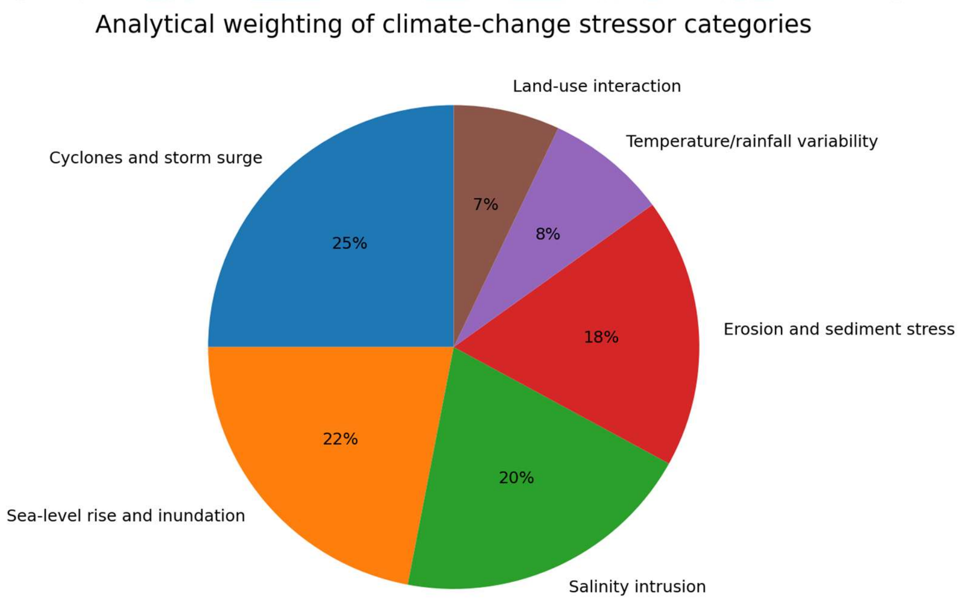
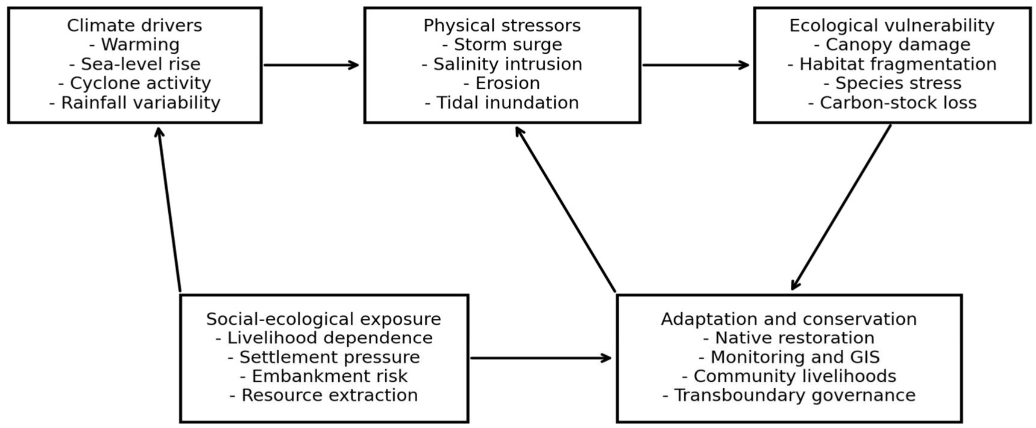


Figure 4: Pie Chart Showing Categories of Climate-Change Stressors

Source note: The pie chart is an analytical weighting based on evidence synthesis, not a measured physical proportion. It is used to communicate relative conservation priority across stressor categories.



Evidence-based monitoring creates feedback for adaptive management and conservation prioritization.

Figure 5: Conceptual Framework Linking Climate Stressors, Ecological Vulnerability, Adaptation and Conservation Needs

Source note: Developed by the author from the vulnerability framework and literature synthesis. The diagram shows how climate drivers operate through physical stressors to produce ecological and social-ecological vulnerability, while adaptation and monitoring provide feedback for management.

Table 6: Adaptation and Conservation Measures for the Sundarbans

Conservation strategy	Implementing agency/stakeholders	Expected benefit	Limitations	Policy relevance
Native-species mangrove restoration	Forest departments, local communities, research institutions	Improves regeneration, shoreline buffering and habitat continuity	Low survival if planted on highly eroding or hydrologically unsuitable sites	High priority for site-specific restoration under MISHTI and related schemes
Hydrology and salinity monitoring	MoEFCC, state agencies, universities, scientific institutions	Detects threshold stress and guides species selection	Requires long-term stations, open data and quality control	Essential for climate-smart mangrove management
Sediment-sensitive shoreline management	Coastal-zone authorities, engineers, geomorphologists	Reduces erosion risk and supports vertical accretion	Hard-engineering structures may shift erosion elsewhere	Needed where mangrove loss is driven by sediment deficit
Cyclone-resilient livelihood planning	Disaster-management agencies, panchayats, NGOs, forest committees	Reduces extraction pressure and improves	Income alternatives must be locally viable	Links ecosystem conservation with social adaptation

Conservation strategy	Implementing agency/stakeholders	Expected benefit	Limitations	Policy relevance
		household recovery		
Remote sensing and GIS monitoring	FSI, universities, space agencies, conservation agencies	Tracks cover, canopy condition, shoreline movement and restoration success	Needs field validation and comparable classification methods	Supports early-warning and adaptive conservation
Blue-carbon assessment and finance	Climate agencies, researchers, conservation finance institutions	Recognizes carbon value and may support restoration funding	Requires rigorous stock estimation and safeguards	Promising for long-term financing if benefits reach communities
India-Bangladesh transboundary cooperation	National governments, forest departments, disaster and research agencies	Improves data sharing, cyclone response, biodiversity protection and integrated delta planning	Institutional coordination can be slow	Critical because the ecosystem is hydrologically connected across borders

Source note: Synthesized from MoEFCC (2025), Forest Survey of India monitoring practice, IPCC adaptation framing and recent Sundarbans climate-risk literature.

8. Results:

The first important finding is that mangrove cover official statistics show a small positive area trend for West Bengal for 2013-2023. The mapped area showed an increment of 22.16 sq km which is 1.06 percent. The positive trend has been noted in various conservation initiatives and ecosystem restoration programmes reported by MoEFCC (2025). It includes afforestation, eco-restoration, and shoreline-oriented groups. Approximately, this change in frequency, a 0.1 to 0.2% rise in the frequency of nuclear kills in the total decades, indicates that this increase should be interpreted cautiously. In deltaic environments, where processes of erosion and accretion cause continuous redistribution of mangrove habitat, it is suggested that the total area change may be less informative than the location and ecological quality of the change.

The second outcome indicates that cyclone exposure continues being a key vulnerability source. According to Bhargava & Friess (2022), Mishra et al. (2021), Amphan is unique because of the large-scale mangrove damage, shoreline loss and vegetation-condition change. Repeated exposure of the Bay of Bengal coast to high-impact storms like Bulbul, Yaas and Remal, also shown The occurrence of such events over a short period leads to higher chances of disturbance in these mangrove stands before their recovery is complete. For seedlings, young stands and eroding shoreline zones, reattacking disturbance is especially important.

The vulnerability of the ecosystem is greatest at the intersection of two kinds of risks. The gradual increase in sea levels and tidal floodings causes the plants to grow under great stress and is a cause for chronic damage. Tropical cyclones and storm surges cause brief damage but fatal damage. Erosion removes habitat, and saline intrusion reduces physiological tolerance and regeneration. The land-use pressure limits the ability of mangroves to migrate and recover. The risk of sea-level rise, cyclone exposure, salinity intrusion, and shoreline erosion are therefore assigned as very high. The implication is not that all places in the Sundarbans are equally vulnerable, but that these stressors can be prioritized for monitoring and conserving planning.

Mapped cover stabilization does not eliminate evidence of forest quality decline, the fourth outcome. According to Ali and Rahman (2025), between 2000 and 2023, the forest stocking and aboveground biomass carbon classes changed considerably. Among the changes was the decline the higher tree-height and higher carbon-stock classes. Changes to the structure of the system can reduce habitat quality and blue-carbon function even when cover extent is stable. Consequently, other variables such as canopy height, biomass, species composition and shoreline position should also be reported.

The fifth result involves adaptation gaps. Government programmes and restoration initiatives are essential but must be linked with site specific vulnerability. Simply planting more mangroves will not solve the problem of erosion unless sediment supply, hydrodynamics and shoreline retreat are taken care of. Likewise, if livelihood alternatives are weak or if embankment failures repeatedly expose households to saline flooding, community adaptation cannot be effective. The results show that adaptation should be integrated across ecology, geomorphology, disaster management and local livelihood planning.

9. Discussion section 9.

Vulnerability of Sundarbans implies ecological importance in conjunction with geomorphic dynamism and high hazard exposure. The narrative of disaster-risk almost always emphasizes the protective value of the system but the forest is also at risk. Storm surges and winds energy are expected to be buffered by mangroves. However, extreme events can damage mangroves, especially where shorelines are already unstable. The reciprocal relationship between mangroves and people is vital to conservation planning, with mangroves protecting people and people protecting mangroves from climate change and unsustainable land use.

The positive area trend in the official cover statistics should be read as likely conservation opportunity and not as total success. MoEFCC (2025) reports West Bengal gaining mangrove cover from 2013 to 2023, which means that restoration and conservation efforts are contributing to area maintenance. Nevertheless, peer-reviewed studies show cyclone impacts, erosion and forest-stock changes are considerably significant. If area is treated as the only outcome, this creates an apparent contradiction. A more accurate view is that conservation stabilizes mapped cover, while climatic stress continues to degrade the condition and resilience of vulnerable segments of forests.

The slow but insistent nature of sea-level rise makes it very important. If sediment accretion, root growth, and landward migration keep pace, mangroves can adjust to rising water levels. Nevertheless, adaptation is limited where embankments, settlements or aquaculture block movement. In those locations, the mangroves are available between rising water and fixed infrastructure. The Sundarbans therefore need land-use planning that goes beyond just maintaining current boundaries to anticipate future migration corridors and sediment maintenance processes.

Cyclones are the fast-disruption aspect of climate risk. The Amphan cyclone demonstrated that a single event can cause extensive forest damage and shoreline loss. According to the literature, the beach erosion caused by cyclones impacted the extent of damage caused by later cyclones. This finding matter because it suggests that vulnerability is historically conditioned. According to a study, mangroves that have been eroding for decades, may become more susceptible to future cyclones even if they are currently mapped. Shoreline change analysis should thus become a regular part of prioritisation for conservation.

Ecological complexities are further compounded by salinity intrusion. Different mangrove species have different tolerance to salinity, with seedlings often being more sensitive than mature trees. If salinity rises slowly, the composition of species may change before total cover. If salinity suddenly rises due to cyclone surge or breach of embankment, regeneration may not succeed in lower niveaux affected areas. Thus, monitoring species composition, seedling survival and soil-water salinity is essential for early detection of ecological transitions.

The dialogue also points out the value of blue carbon. Mangrove conservation efforts are often justified on the basis of their carbon storage ability. Carbon accounting, however, should allow for more than just tree cover. Ali and Rahman's (2025) finding of declining higher carbon-stock classes indicates that climate and disturbance effects may reduce carbon quality even cover persists. For restoration interventions to be effective, the blue-carbon finance should combine punctilious measurement, permanence safeguards and benefit-sharing with communities.

Continuous reclamation, conservation through monitoring and coastal zone management initiatives are positive efforts. Nevertheless, there are obstacles. The failure of restoration can arise from species not being picked based on salinity-inundation. Seawalls can protect settlements but may change sediment dynamics and block mangrove migration. If household risk, debt, employment and disaster recovery are adequately addressed, community programmes can help mitigate stress. Such constraints demonstrate that conservation cannot be disjoined from social adaptation.

Cross border collaboration is essential. The Sundarbans, which are shared between India and

Bangladesh, hydro-ecological-meteorological processes cross political borders. A set of harmonized protocols in case of cyclones, tiger habitats, fisheries, salinity, sediment research and remote-sensing products. A joint monitoring platform that includes Landsat and Sentinel satellites, GEDI, field plots and hydrological stations could improve comparability and early warning capacity.

10. Conservation Needs and Policy Recommendations 10

1. Use native species and conducting site-specific hydrological assessment for strengthening the mangrove restoration. Planting should happen mainly in zones expected to have long-term survival conditions in elevation salinity and sediments.
2. There should be improved long-term monitoring of mangrove cover, canopy height, salinity, erosion, sediment accretion, biomass and biodiversity. Incorporate forest condition indicators into official reporting, not just area covered.
3. Make community-managed conservation initiatives more robust through diversification of livelihoods, culture-proof income opportunities, participatory monitoring and benefit-sharing of restoration or blue-carbon project.
4. Make climate adaptation integral to coastal-zone management by identifying future mangrove migration corridors, restricting high-risk construction and improving ecosystem sensitive embankment planning.
5. Encourage cooperation between India and Bangladesh on issues of hydrological data, impact assessment of cyclones, biodiversity conservation as well as tiger habitat protection and climate adaptation.
6. Endorse blue-carbon record-keeping only when measurement, verification, permanence and community protections are robust. The objectives of biodiversity and livelihood should not be replaced by carbon finance.
7. Create livelihood strategies for fishing, honey collection, tourism, agriculture, and aquaculture, especially in high-exposure blocks.
8. Prevent land-use change that degrades mangrove habitats, including fragmentation, reducing sediment connectivity or salinity intrusion, should be restricted.
9. Enhance early warning mechanisms, streamline evacuation strategies, and conduct swift ecological evaluations after cyclones to quickly assess damage to forests, shoreline erosion, and salinity effects.
10. Use of GIS, Remote Sensing, LiDAR, Drone Surveys, Permanent Sample Plots and Field-based validation to promote ecological research for bridging the gap between mapped cover and ecological condition.

11. Study Limitations or Constraints:

- The reliance of research on secondary data means it cannot replace field-based ecological measurement.

- The assessment of forest cover is based on a statistical analysis of remote-sensing classification methods, which may differ across years. These methods, however, may not detect degradation at the species level, or discrimination based on sub-category or structure.
- The cyclone damage impact score is a score which is based on several instances of official and published evidence.
- Data regarding salinity response at species-level and long-term regeneration is scanty for much of the Sundarbans.
- Different land-use decisions have affected the riverscape since thousands of years and more so in the last hundred years.
- The Sundarbans are transboundary, and India-only cover statistics provides a limited view of the ecosystem.

12. Possibilities to Explore for Future Research.

- Assessment of ecological vulnerability based on field-based salinity, topography, sediment accretion, soil carbon and seedling survival
- Studies on salinity tolerance and regeneration for major mangroves.
- Research on household adaptation that is linked to dependence on livelihood, cyclone recovery, migration and conservation participation
- Use GIS to Model Shoreline Changes from Sea Level Rise.
- To estimate blue carbon stock, field plot, LiDAR, soil core and remote sensing have been integrated.
- Long-term biodiversity monitoring of fish, crustaceans, mammals, and key indicator species.
- Analysis of India's and Bangladesh's Sundarbans using harmonized protocols

13. In conclusion:

The Sundarbans mangrove ecosystem faces a great and multidimensional threat of climate change. Research presented in this paper shows that sea-level rise, tidal inundation, salinity intrusion, cyclones, storm surge, shoreline erosion and land-use pressure interact to produce high ecological vulnerability. Official data shows that there was a modest increase in mangrove cover in West Bengal between 2013 and 2023. However, this positive area trend should be interpreted with evidence of cyclone damage, erosion and change in forest structure. The area alone does not define a resilient Sundarbans.

The results of the present analyses point to one overarching conclusion; that conservation strategy should shift from a cover-maintenance approach to an ecosystem-function resilience approach. Monitoring canopy condition, biomass, sediment elevation, salinity, species composition, regeneration and shoreline movement is required. Cyclone Amphan displays how quickly these extreme events can play havoc with mangrove systems, whereas longer-term sea-level rise and salinity change showcase the need for anticipatory adaptation. Restoration programs should use native species, match planting sites to hydrology and sediment conditions, and avoid a narrow focus on plantation area as a measure of success.

The Sundarbans exhibit characteristics of a social-ecological system. The ecological outcome in the Brahmaputra basin influenced by huge factors like human livelihoods, embankment management, disaster preparedness and transboundary governance. Therefore, conservation must include community-based adaptation, livelihood diversification, blue-carbon safeguards, early-warning systems, and Indo-Bangla cooperation. The Sundarbans future hinges on integrated planning that sees mangroves as living climate infrastructure, biodiversity habitat, carbon reservoir and livelihood-supporting systems. Let us protect this ecosystem not only as conservation, but as a climate resilience strategy in one of the most vulnerable coastal deltas in the world.

References:

Ali, Y., & Rahman, M. M. (2025). Quantifying forest stocking changes in Sundarbans mangrove using remote sensing data. Science of Remote Sensing, 11, 100181. https://doi.org/10.1016/j.srs.2024.100181

Bhargava, R., & Friess, D. A. (2022). Previous shoreline dynamics determine future susceptibility to cyclone impact in the Sundarban mangrove forest. Frontiers in Marine Science, 9, 814577. https://doi.org/10.3389/fmars.2022.814577

Forest Survey of India. (2021). India State of Forest Report 2021. Ministry of Environment, Forest and Climate Change, Government of India.

Forest Survey of India. (2023). India State of Forest Report 2023. Ministry of Environment, Forest and Climate Change, Government of India.

India Meteorological Department. (2019a). Extremely Severe Cyclonic Storm Fani over eastcentral equatorial Indian Ocean and adjoining southeast Bay of Bengal, 26 April-4 May 2019: A report. Regional Specialized Meteorological Centre, New Delhi.

India Meteorological Department. (2019b). Very Severe Cyclonic Storm Bulbul over the Bay of Bengal, 5-11 November 2019: A report. Regional Specialized Meteorological Centre, New Delhi.

India Meteorological Department. (2020). Super Cyclonic Storm Amphan over the southeast Bay of Bengal, 16-21 May 2020: A report. Regional Specialized Meteorological Centre, New Delhi.

India Meteorological Department. (2021). Very Severe Cyclonic Storm Yaas over the Bay of Bengal, 23-27 May 2021: A preliminary report. Regional Specialized Meteorological Centre, New Delhi.

India Meteorological Department. (2022). Cyclonic Storm Sitrang over the Bay of Bengal, 22-25 October 2022: A brief report. Regional Specialized Meteorological Centre, New Delhi.

India Meteorological Department. (2024). Severe Cyclonic Storm Remal over the Bay of Bengal: Tropical cyclone advisory and technical bulletins. Regional Specialized Meteorological Centre, New Delhi.

Intergovernmental Panel on Climate Change. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844

Mishra, M., Acharyya, T., Santos, C. A. G., da Silva, R. M., Kar, D., Kamal, A. H. M., & Raulo, S. (2021). Geo-ecological impact assessment of severe cyclonic storm Amphan on Sundarban mangrove forest using geospatial technology. Estuarine, Coastal and Shelf Science, 260, 107486. https://doi.org/10.1016/j.ecss.2021.107486

Ministry of Environment, Forest and Climate Change. (2025, August 11). Parliamentary question: Conservation of the Sundarbans Mangrove Ecosystem. Press Information Bureau, Government of India.

Mondal, B., Saha, A. K., & Roy, A. (2021). Spatio-temporal pattern of change in mangrove populations along the coastal West Bengal, India. Environmental Challenges, 5, 100306. https://doi.org/10.1016/j.envc.2021.100306

Press Information Bureau. (2024, December 21). Union Minister Bhupender Yadav releases India State of Forest Report 2023. Government of India.

UNESCO. (2024). The Sundarbans: World Heritage and climate resilience information. United Nations Educational, Scientific and Cultural Organization.

UNEP-WCMC. (n.d.). The Sundarbans: World Heritage datasheet. United Nations Environment Programme World Conservation Monitoring Centre.

World Bank. (2020). Coping with climate change in the Sundarbans: Lessons from multidisciplinary studies. World Bank.

World Bank Group & Asian Development Bank. (2021a). Climate risk country profile: Bangladesh. World Bank Group.

World Bank Group & Asian Development Bank. (2021b). Climate risk country profile: India. World Bank Group.