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A twenty-five year synthesis of mangrove ecosystem dynamics in the Sundarbans, West Bengal, India: A review

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Abstract

The Sundarbans, one of the largest contiguous blocks of mangroves in the world, has experienced a significant environmental shift over the past 25 years. Formerly boasting a rich diversity of mangrove species, the area had been indispensable for coastal protection, conservation of ecological system, and maintaining local people's lives. In recent decades, escalating human pressures such as deforestation, aquaculture expansion, and industrial development have resulted in considerable loss and fragmentation of mangrove habitats. Today, rising seas, changes in salinity patterns, frequent and intense extreme weather events and pollution in all its varieties threaten the system's recovery by destabilizing it. Concurrently, the role of mangroves in carbon capture and disaster risk reduction is receiving increasing attention. Due to these threats, various conservation and restoration programs such as community-based projects and large-scale afforestation initiatives—have been successful in their attempts. In the future, climate change is likely to increase vulnerability of Sundarbans complex and changes in species composition and ecosystem processes may be driven here. However, innovative restoration methods integrated with enabling policies and increased active involvement of local populations offer better prospects for maintaining the ecological status and functionality of the area. With this context, we collate synopsis about the past, present and future conditions of the Sundarbans mangrove habitat that accentuate the urgent attention these composite ecosystems require through integrated adaptive management to sustain their resilience to climate change.

Keywords: Indian Sundarbans, mangrove ecosystems, climate change, biodiversity

Introduction

Mangrove forests, are one of the most remarkably biodiverse and ecologically functional biospheres; belonging to the most intricate and productive ecosystems on planet Earth (Bhagarathi & DaSilva, 2024; K *et al.*, 2024; Rahmadi *et al.*, 2023) ^[6, 24, 39]. They are key assets for the protection of coastlines, the preservation of biodiversity and carbon storage, thus contributing significantly to climate change mitigation (Blasco, Dewan 2000; Blanco *al.*, Cuenca-Ocay 2004) ^[10]. In India, the vast contiguous

mangrove forest is located within the state of West Bengal and it is known as the *Sundarbans*. This region also serves as an important habitat for numerous species such as the Royal Bengal Tiger (Ghosh *et al.*, 2021) ^[17]. Furthermore, Sundarbans act as a potent sentinel against the powerful tropical cyclones, which ensures the survivability of the highly populated lower Gangetic plain, adding the utmost importance towards protecting the livelihoods of millions of people living in the coastal areas.

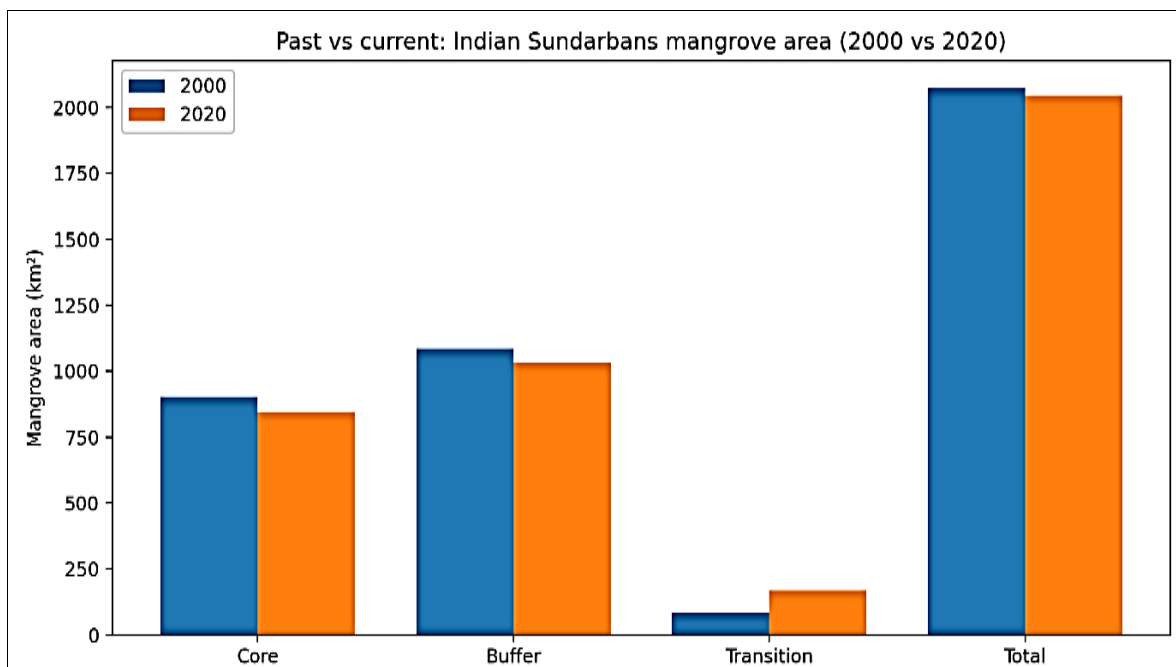


Fig 1: Comparison of mangrove area in the Indian Sundarbans between 2000 and 2020, showing variations across core, buffer, and transition zones. The data indicate a diminishing trend in core mangrove forests and an expansion of transitional areas over the two-decade period. (Source: Samanta *et al.*, 2021) ^[46]

Over the decades various factors such as coastal erosion, salinity intrusion and anthropogenic pressure have resulted in significant depletion of mangrove areas and species diversity of the Sundarbans (Islam & Bhuiyan, 2018; Kanan *et al.*, 2023; Mahato, 2024; Mondal *et al.*, 2021; Neogi *et al.*, 2017; Sahana *et al.*, 2022 Samanta *et al.*, 2021) ^[22, 25, 33, 34, 46, 36, 44]. The analysis of mangrove area coverage in Indian Sundarbans from 2000 to 2020 shows changes in the core, buffer and transition areas for the Indian part. The decline of the core mangrove with a consequent increase in the transitional state is clear from this analysis (see Figure 1) (Jayanthi *et al.*, 2022; Samanta *et al.*, 2021) ^[23, 46]. Current field observations and second-hand information suggest that loss of mangrove was still occurring after 2020; the effects were particularly pronounced by around 2025. The prime objective of this review is to assemble the existing knowledge derived during the last 25 years that depict dynamics in mangrove ecosystems within the Sundarbans. It aims to assess long-term trends, identify the current pressures on the ecosystem and predict future changes, particularly those underpinned by climate change. By reviewing past conservation efforts and ongoing restoration, we hope to point out some potential strategies for reinforcing ecosystem resilience in the face of increasing environmental stress. Mangroves are crucially important to the maintenance of biodiversity, serving as major spawning areas for numerous fish species and significant resting and nesting grounds for migrating birds (Duhita & DaSilva *et al.*, 2024; Payán-Alcacio *et al.*, 2021; Raihan, 2023; Waleed *et al.*, 2024) ^[6, 37, 41, 53]. They also act as important carbon sinks, with dense root structures that store a large amount of carbon which would otherwise further contribute to global warming (Alongi 2014; Bhagarathi & DaSilva 2024; Bourgeois *et al.*, 2024; Hossain *et al.*, 2025; Rahman *et al.*) ^[1, 6, 8, 21, 40]. In the face of increasing climate change, mangroves stand out as one of

the most effective forms of natural systems mitigating its effects especially along coastlines (Bolívar-Anillo *et al.*, 2020; Dasgupta *et al.*, 2019; Gijssman *et al.*, 2021; Lee *et al.*, 2025; Macreadie *et al.*, 2021; Moustafa *et al.*, 2023; Rudianto *et al.*, 2022; Sunkur *et al.*, 2023) ^[14, 7, 18, 28, 32, 35, 42, 51]. This use has made the significance of these ecosystems more apparent, which clearly indicates the urgency and demand for further research and adaptable management practices to protect their ecosystem services and associated economic values (Gijssman *et al.*, 2021; Hespen *et al.*, 2022; K *et al.*, 2024; Lovelock *et al.*, 2022) ^[18, 52, 31].

Materials and Methods

Data collection

The data for this review paper were collected from a range of historical and contemporary sources. Historical data include satellite imagery, remote sensing data, and field surveys conducted in the Sundarbans region over the past 25 years. These sources of information provide in-depth comprehension of variations in mangrove cover, species distribution, and the ecological vigour of the region. Additionally, we reviewed government reports, local environmental assessments, and relevant scientific literature pertaining to mangrove conservation, restorative efforts, and diminishing of threats. Recent findings from peer-reviewed journals, associated with ecological and meteorological aspects, provided the freshest/latest updates on current threats, ongoing conservation initiatives, and future projects culminating in an ecologically protected Sundarbans.

Selection criteria

The selection of studies for this review was guided by specific inclusion criteria to ensure that the gathered data are relevant, reliable, and scientifically viable. The principal selection criteria were:

1. Relevance: This review considered only research

undertaken on the mangrove ecosystems in Sundarbans and which had determined their natural/human-induced causative factors. Studies on climate change impact were preferred as well as on conservation programmes, biodiversity and ecosystem services.

2. **Geographical focus:** The study area covered the Indian Sundarbans mangroves situated between latitudes 21°32' N and 22°40' N and longitudes 88°05' E and 89°51' E in West Bengal, India; the region consists of

two districts namely North Twenty-four Parganas (N24P) and South Twenty-four Parganas (S24P). The SB Core and Buffer Zone consist of the Sundarbans Biosphere Reserve, with different levels of conservation and human use, which served as a rationale for the study area (Figure 2). This area has unique ecological and socio-economic features of distinction from other mangrove horribilis in the world.

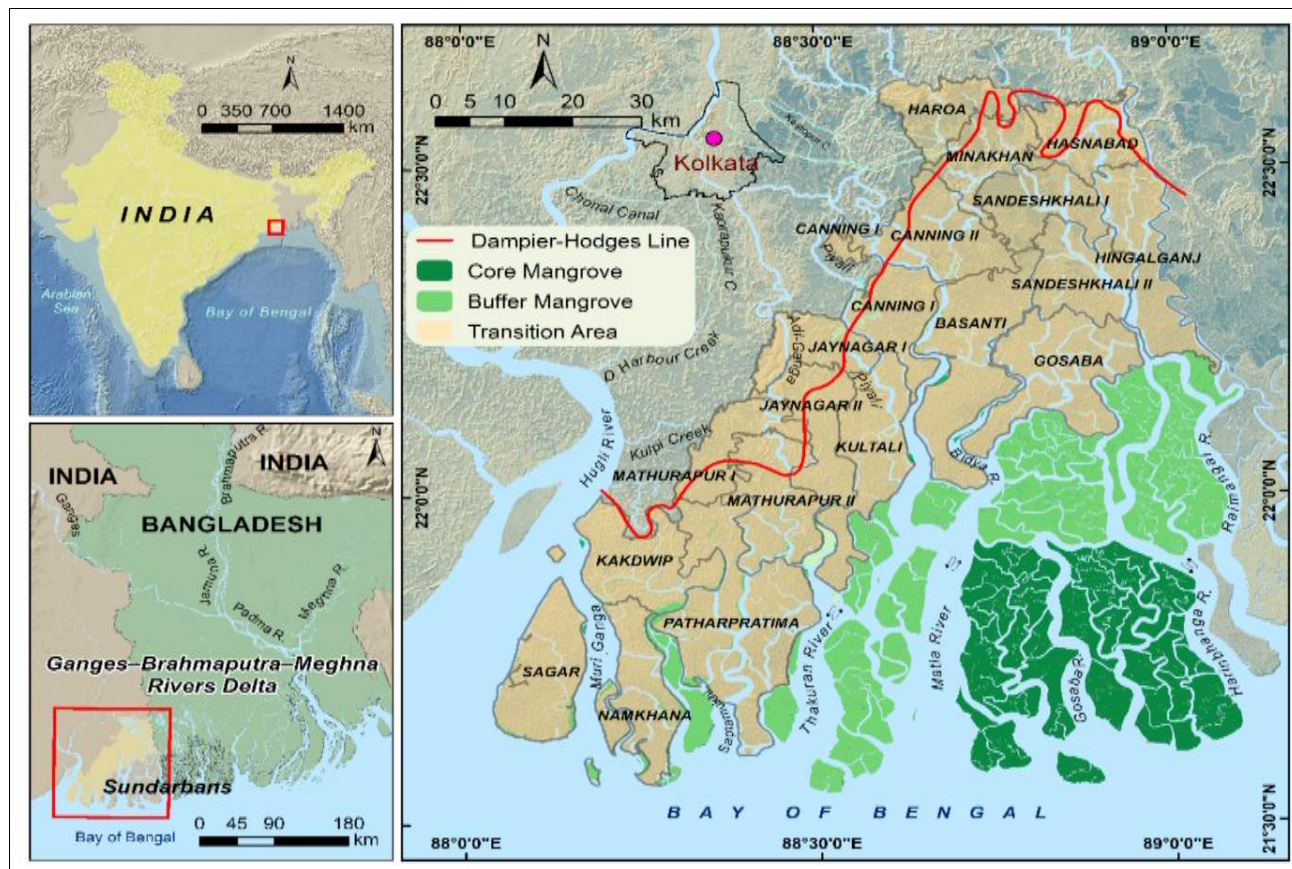


Fig 2: Location map of the Indian Sundarbans showing the study area within the Ganga-Brahmaputra-Meghna delta region. The figure illustrates the spatial extent of the Sundarbans Biosphere Reserve, including the core, buffer, and transition zones, along with major rivers, distributaries, administrative blocks, and the Dampier-Hodges Line. (Source: Samanta *et al.*, 2021) ^[46]

3. **Scientific rigor:** We included papers from peer-reviewed journals, influential reports from governments, and leading local research that adhered to sound scientific methodology (*i.e.* field surveys, modelling methods and remote sensing techniques).

Methodological Approach

Collections of information were synthesised using a comparative and temporal analysis method, including:

1. **Comparative analysis:** Comparative analysis of Past and present data sets was compared to identify overall trends and patterns of mangroves change in extent, species composition and ecosystem processes occurring over the last 25 years. The satellite images and field survey data was analysed in combination with

recent observations, in order to identify major change within the region.

2. **Temporal trends:** We examined how the Sundarbans mangrove ecosystems have changed based on widely ranging research data sets. Our case studies specifically highlighted the development of salinity, deforestation and storm impact issues alongside conservation responses and policy change.
3. **Integrated synthesis:** Data gleaned from the different sources of information were integrated into a common picture of mangrove dynamics. Such an investigation involved integrating knowledge from remote sensing, ground observations, regional studies as well as global climate models to develop a comprehensive view of the past, present and future.

Table 1: Data collection and methodology for the review of mangrove ecosystem dynamics in the sundarbans

Category	Data Source	Time Period	Details
Historical Data	Satellite Imagery, Remote Sensing Data, Historical Field Surveys	1990s - 2000s	Satellite images and remote sensing data were used to track the extent and distribution of mangrove cover. Historical field surveys provide insights into species diversity, forest cover, and ecological conditions during the past decades.
Government Reports	Indian Ministry of Environment and Forests (MoEF), West Bengal Forest Department, Indian Remote Sensing (IRS)	1995 - Present	Government reports provide data on conservation policies, mangrove afforestation projects, and coastal management efforts, including annual forest cover assessments, restoration activities, and threats from human activities like deforestation and pollution.
Local Environmental Studies	NGO Reports (e.g., Sundarbans Mangrove Conservation Project), Local University Research, Environmental Audits	2000s - Present	Local environmental studies provide specific insights into ongoing restoration efforts, community participation in conservation, and local threats such as shrimp farming, over-extraction of resources, and pollution.
Peer-reviewed Journals	Ecological Journals (e.g., <i>Estuarine, Coastal and Shelf Science</i>), Climate Science Journals (e.g., <i>Nature Climate Change</i>)	2000s - Present	Peer-reviewed studies provide updated scientific knowledge on the current state of the mangrove ecosystem, with an emphasis on climate change impacts, sea-level rise, salinity changes, and mangrove resilience.
Modeling and Forecasting Studies	Climate Models, Ecosystem Simulation Tools	2010s - Present	Climate models and ecosystem simulation tools help project future changes in mangrove ecosystems, including species distribution, sea-level rise effects, and the effect of severe weather events. These studies are used to forecast future scenarios for the Sundarbans.

Explanation of the data

- 1. Historical data (Satellite imagery, remote sensing data, historical field surveys):** Satellite imaging and remote sensing data are the main equipment to capture changes in the range of mangrove and spatial position over a span of 25 years. They provide visual evidence of both forest cover loss and gain as well as changes in surrounding landscapes that may not be obvious through field surveys alone. Prior field surveys yield on-the-ground information about species composition and condition of an ecosystem, serving as a point of comparison for present-day environmental conditions.
- 2. Government reports:** Government reports including those by Indian Ministry of Environment and Forests (MoEF) and West Bengal Forest Department are reliable sources of the mangrove ecosystem condition. These accounts also cover continuing conservation programs, evaluating forest cover and government strategies for the protection of mangrove. Furthermore, official satellite and field information for the surveillance of CNC activities and their impacts in the environment are highly valuable.
- 3. Local environmental studies:** Local NGOs and university research in the area tend to concentrate on specific conservation projects within the Sundarbans, e.g. the Sundarbans Mangrove Conservation Project or university research performed by institutions located in West Bengal. These reports often focus on regional threats, such as human activities (e.g. shrimp farming and unsustainable fisheries) and the difficulties of mangrove restoration in places degraded by environmental harm.
- 4. Peer-reviewed journals:** Scientifically validated information from peer-reviewed journals: The best

available information to date on mangrove ecosystems. Research from these sources may cover many different aspects, including the role of mangroves in protecting coastlines, soaking up carbon and how they are affected by climate change. These journals also cover developments of conservation approaches, the effects of sea-level rise and how mangroves work towards counteracting extreme weather events such as cyclones.

- 5. Modelling and forecasting studies:** Modelling and forecasting studies are used to predict future changes in the Sundarbans ecosystem. Climate models and ecosystems simulations can provide estimations on future mangrove extent, species occurrence, and the likely ramifications of climate change - including sea level rise and increasing salinity. These predictions are important in understanding the long-term survivability of mangroves, and also in developing adaptation measures.
- 6. Past scenario (25 Years ago) mangrove coverage:** 25 years ago, the Sundarbans Submerged in 15-km uphill area (Figure 3) Approximately 4,260 of sq. km area along West Bengal coast was occupied by sprawling mangrove ecosystem of the Sundarbans delta creating a rich but fragile habitat (Banerjee *et al.*, 1994) [3]. The mangrove forests consisted primarily of Sundari (*Heritiera fomes*), Goran (*Ceriops decandra*) and Kankra (*Bruguiera gymnorrhiza*). These species established a biomass rich forest ecosystem providing habitat to numerous animals and playing an important role as a natural barrier to the coasts in relation to storms or flooding (Ghosh *et al.*, 1999) [16]. But still, even at that time, human encroachment and natural threats already affecting the ecosystem.

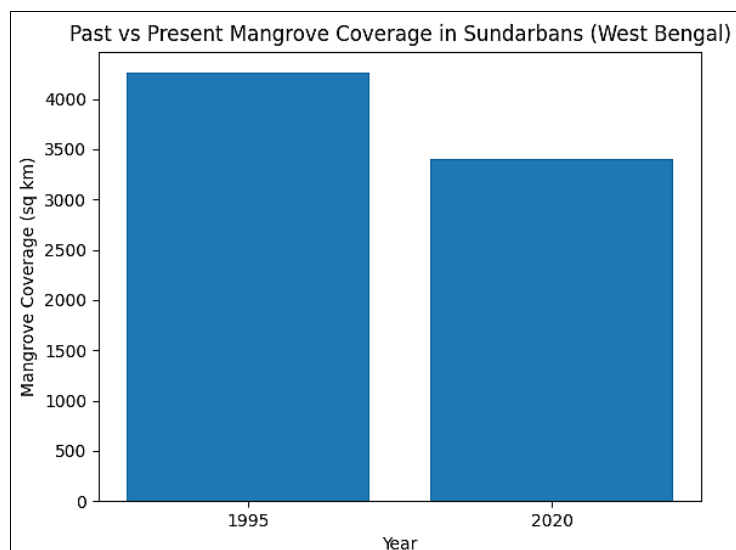


Fig 3: Comparison of mangrove forest coverage in the Sundarbans, West Bengal, between 1995 and 2020. The data indicate a decline in mangrove cover over the last 25 years, influenced by increasing anthropogenic pressures and climate-induced environmental changes. (Source: Banerjee *et al.* 1994; Dahdouh-Guebas *et al.* 2017) ^[3, 11]

Challenges

The mangroves had suffered from a number of pressures, including the spread of human intervention on them, most notably settlement, deforestation and pollution from agriculture and industrialisation. The alteration of flourishing mangroves to decadent shrimp ponds and various types of agricultural practices led to extensive natural habitat loss. Further, the release of raw sewage from neighbouring towns into coastal waters resulted in a further decline in water quality (notably the dissolved O₂ levels) thereby affecting very delicately the equilibrium of this mangrove ecosystem (Choudhury, 2002) ^[9]. Although the forests suffered extensive damage through natural phenomena such as cyclones and tidal surges, there was recovery being showcased with resilience of the mangroves.

Conservation efforts

In response to these additional threats, early conservation measures began to take shape. The first mangrove reforestation projects have been initiated by the West

Bengal Forest Department, where Sundari and Goran species were planted in degraded sites. However, these projects were in the initial phase of implementation and general conservation plans had not been developed yet.

Current scenario

Present threats

The Sundarbans mangrove ecosystem is currently grappling with heightened and varied challenges, largely due to climate change. Global warming has led to rising sea levels, which are already flooding low-lying mangrove regions and altering species distribution (Dutt *et al.*, 2015) ^[15]. Additionally, the increase in average temperatures has disrupted the thermo-sensitive growth cycles of several mangrove species, reducing their ability to withstand environmental changes. Pollution, particularly from adjacent industrial and agricultural runoff, continues to deteriorate water quality, adding further strain to the mangrove ecosystem (Saha & Mishra, 2019) ^[43].

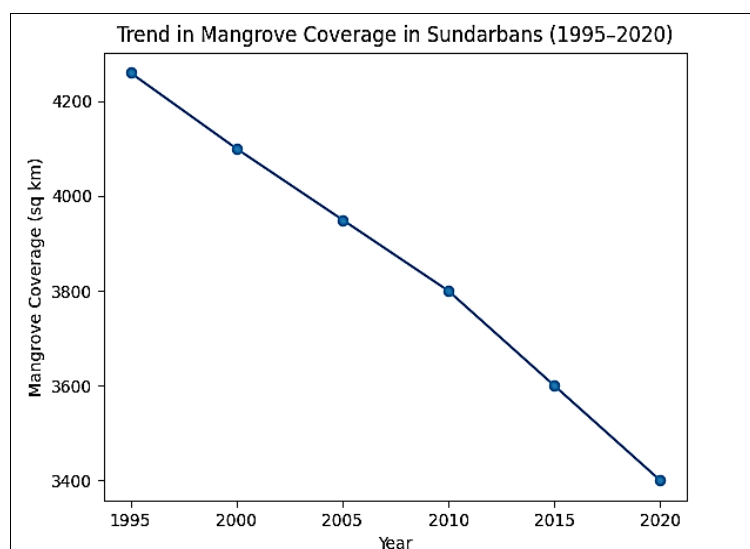


Fig 4: Changes in mangrove coverage (sq. km) in the Indian Sundarbans between 1995 and 2020. (Source: Banerjee *et al.* (1994); Dahdouh-Guebas *et al.* 2017) ^[3, 11]

Furthermore, mangrove habitats have been eliminated due to human interventions such as urban expansion and infrastructure development. By comparing map-based estimates of mangrove land, deforestation and species richness between 1995 and 2020 in the Sundarbans, West Bengal, India. We demonstrate that levels of mangrove cover have globally declined over this time period due to a combination of human activity and climate related environmental effects.

Advancements

There are many advancements in the field of protection and conservation. The Indian government has also begun large-scale restoration of mangroves in partnership with local NGOs, targeting the most deforested and degraded stretches (Ghosh *et al.*, 2021) ^[17]. In addition, the use of modern conservation technologies like drones and satellite imagery improve tracking the health and expansion of mangroves (Sharma & Singh, 2020) ^[48]. A lot of conservation efforts also did by several NGOs, CBOs etc. Rehabilitation work, including in these poor areas such as Chhotomollakhali gram panchayet under Gosaba Block has seen good tree plantation success by a Kolkata based NGO named Change Initiatives for biodiversity revival. Change Initiatives has planted nearly 2.12 lakh mangrove saplings along the coastline of Chhotomollakhali since 2021. The plantation has now developed into a dense mangrove forest, protecting the area with a survival rate of over 80%.

Global/regional statistics: Yet even the Sundarbans are not exempt from the global wave of destruction sweeping across mangrove forests. Global assessments of mangrove cover indicate that approximately 35% of the world's mangrove forests have been lost within recent decades (Giri *et al.*, 2011) ^[20]. In contrast, the Sundarbans have experienced a less dramatic but still alarming decline (about 20% of total mangrove cover over two decades (Dahdouh-Guebas *et al.*, 2017) ^[11]).

Response to climate change

Sea level rise: Rising sea-levels is the most pronounced

effect of climate change on Sundarbans mangroves.

Since mangrove forests cover low lying coastlines (0.3-0.5MSL), without further intervention, current estimates indicate that the region could lose 50% of its mangrove habitat by 2050 (Dasgupta *et al.*, 2017) ^[13]. Sea-level rise renews saline encroachment in the coastal zone, thereby making growth nearly impossible of many mangrove species at their native place (Sahoo *et al.*, 2020) ^[45].

Salinity changes

Salinity fluctuates also due to changes in the freshwater flows upstream human extractions and altered courses of monsoon, which adversely impact the welfare of mangrove ecosystems. Mangrove species are very responsive to salinity changes, with perturbations in their levels leading to decrease in mangrove growth, reproduction and higher susceptibility to pathogens (Kumar *et al.*, 2019) ^[27].

Extreme events

Mangrove forests have historically served as natural barriers to cyclones and storm surges. However, increasing frequency and intensity of extreme weather events due to climate change are putting enormous pressure on these ecosystems. Studies show how mangroves in the Sundarbans reduce cyclonic wind and storm surge impacts, protecting coastal people from floods and erosion (Spalding *et al.*, 2014) ^[49]. As cyclones strengthen, the importance of mangroves acting as buffers has never been greater.

Future prospects

Predictions

Projections suggest that climate change will further affect the Sundarbans mangrove system, with higher sea-levels and temperatures threatening overall forest integrity. Mangrove forests are directly impacted by rising sea level; with some of the few options available being migration inland or changes in species. Such changes could change important wildlife habitat and the ecosystem services provided by the mangroves.

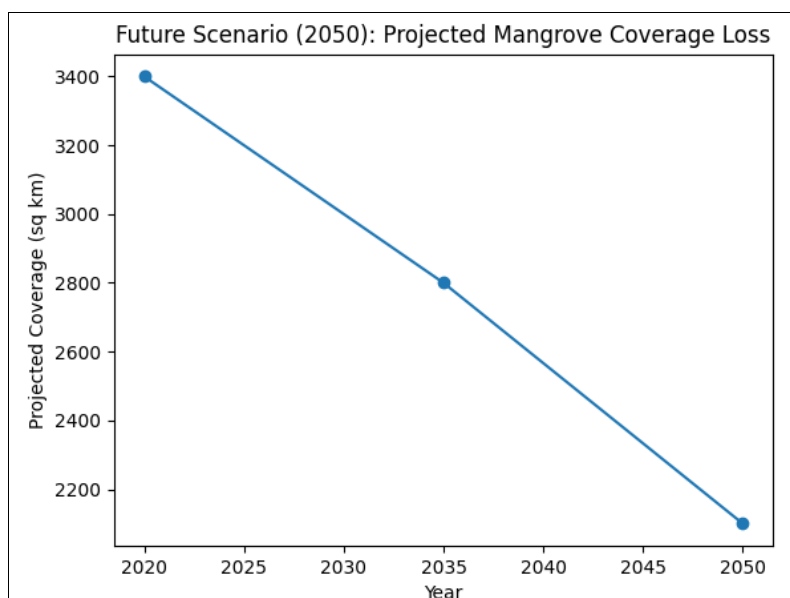


Fig 5: Projected decline in mangrove forest coverage in the Sundarbans under future climate change scenarios up to 2050, highlighting potential losses due to sea-level rise and increased salinity intrusion. (Source: Dasgupta *et al.* 2017; Bhosale *et al.* 2016) ^[13]

Restoration techniques

Innovative restoration methods such as assisted migration (introduction of climate-adapted species in new areas) have also been suggested to tackle these challenges, together with the application of bioengineering techniques to enhance the root systems of mangrove canopies (Pereira *et al.*, 2021)^[38]. Species that are more suitable to saline conditions and extremes of weather are also being planted with a view to establishing more resilient mangrove.

Policy frameworks

In the long term, policy frameworks must be adapted to meet conservation and climate adaptation requirements in tandem. Climate change estimates need to be integrated into mangrove management for future policies and focus in restoration and protection of forest existing, and sustainable coastal development (Liu *et al.*, 2020)^[30]. Furthermore, the mangroves will have to be saved through mainstreaming climate change adaptation into country specific environmental policies.

Community involvement

Man, and Nature are intertwined. The former can exist without the latter but the reverse is not true. In order to coexist, local communities should feature centrally in the conservation of mangroves, as both custodians and beneficiaries of the eco-system. In areas such as Chhotomollakhali Gram Panchayat under Gosaba Block, community-based projects were successful in the restoration of degraded lands because local natives were involved in planting and protecting mangroves (Sarkar *et al.*, 2018)^[47]. Community-wide participation in sustainable livelihood programmes, such as ecotourism and sustainable fisheries, can help to generate alternative sources of income and densify mangroves.

Ecological and economic importance

Biodiversity

Mangroves are home for numerous species including fish, crustaceans, molluscs and various bird species. The mangroves of Sundarbans are a distinct region that have types of life forms and biota which play a vital role in maintaining the local ecological balance. The mangroves also act as reproduction and nursery habitat for many fish species of commercial interest (Leroy *et al.*, 2018)^[29].

Carbon sequestration

Mangroves are effective carbon sinks and sequester a significant amount of carbon in their biomass and soil. Such capability of carbon sequestration is significant to alleviating climate change by lowering atmospheric concentrations of carbon. The Sundarbans mangroves are one of the most efficient carbon sinking ecosystems and thus their protection, conservation and restoration is vital in the global climate change context (Donato *et al.*, 2011)^[40].

Livelihoods

The mangrove swamps in the estuarine areas provide both direct and indirect economical support for livelihood of millions of people through fishing, apiculture, and ecotourism. In the Sundarbans, the local inhabitants depend on the mangroves for their sustenance, with fishing being their chief occupation. In addition, ecologically sustainable

tourism has expanded in recent years, creating additional earnings and strengthening conservation (Sarkar *et al.*, 2020)^[47].

Disaster mitigation

Mangroves serve as sand dunes against the ravages of coastal flooding, storm surges and cyclones — all of which are increasingly severe thanks to climate change. Since healthy mangrove ecosystems can protect from tropical cyclonic storm surges, decrease wave energy, and minimize coastal damage (Kathiresan & Rajendran, 2005)^[26], it has been suggested through studies that these disasters could be lessened impacts. Amidst climate change, the contribution of mangroves to reduction of ecological risks becomes more evident.

Conclusion

Bringing together the past, present, and projected future of the Sundarbans mangrove ecosystem underscores how vital these coastal forests are for biodiversity conservation, climate regulation, and reducing disaster risks. Historically, the Sundarbans mangroves were extensive and healthy, providing various types of ecological services that supported numerous plant and animal species. But over the last quarter of a century, growing human pressure from settlement, logging and pollution have gradually eroded these systems. Today sea-level rise due to climate change, salinity changes and the increased frequency of extreme weather events pose serious threats to mangroves' survival and ecological functioning.

Against this crescendo of pressures, recent advances in conservation and active restoration have enabled the promotion of recovery at degraded sites with positive results already evident at places including Chhotomollakhali Gram Panchayat under Gosaba Block. In the future, climate model projections indicate that pressures on the Sundarbans mangroves will increase further indicating an urgent need for adaptive anticipatory management. State-of-the-art restoration approaches — such as assisted migration and introduction of climate-adapted mangrove species — with more efficient policy instruments, need for increased community involvement will be necessary to save these vital coastal assets.

Furthermore, continued scientific research is necessary to monitor and predict how climate change will impact structure and function of mangroves and their distributions. Sustaining the long-term survival of mangrove ecosystems requires a comprehensive approach that supports definitive policy frameworks with climate adaptation, catalyses community-based conservation, and utilizes scientific progress to improve restoration efforts. By coherently implementing these measures, we will strengthen the resilience of mangroves to existing environmental change and protect the important ecosystem services that they provide to nature and people.

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