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ECOSYSTEM AT THE EDGE: A COMPREHENSIVE REVIEW OF THE INDIAN SUNDARBANS MANGROVE FOREST

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Abstract: *The Indian Sundarban mangrove forest is the largest single tract in the world's largest deltaic mangrove ecosystem & one of unique biogeographical zone at the confluence of Bay of Bengal. This is a very productive and biodiverse habitat performing various ecological, economic, and protective functions. But the region has been long suffering from the effects of natural forces and anthropogenic pressures, such as deforestation, climate-induced sea level rise, salinity ingress, and shoreline erosion. Recently, remote sensing technologies, vegetation indices, and long-term monitoring have been applied to track forest health and spatiotemporal changes. Here we review the major findings of multidisciplinary studies in these forests to provide a unified understanding of the status, dynamics, and conservation issues faced by this forest. There is also a discussion of pragmatic and community-inclusive approaches to sustainable management, and policy-aligned strategies that draw on scientific insights and real-time monitoring.*

Keywords: *Indian Sundarbans, mangrove forest, biodiversity, shoreline change, remote sensing, salinity stress, forest management, sustainable conservation.*

1. Ecological Significance and Biodiversity of the Indian Sundarbans

1.1 Overview of the Mangrove Ecosystem

Along with the Rann of Kutch, Indian Sundarban mangrove forest is the center of largest contiguity of tidal halophytic vegetation in the world and third part of Ganges–Brahmaputra–Meghna delta system. This sedimentary deltaic area developed over thousands of years is a dynamic zone at the juncture of land and sea, providing the habitat for a diverse estuarine ecosystem. Its vicinity along the northern periphery of the Bay of Bengal over ~ 4260 km^2 in India is caught in a high tidal amplitude zone where monsoonal flooding is common making it both ecologically buoyant and climatically susceptible [2].

The Indian Sundarbans has a tropical humid climate with an average rainfall of 1,500–2,000 mm per year, mainly due to the southwest monsoon. The temperature can be between 12°C in winter and over 35°C in summer. These conditions, combined with a complex web of estuarine rivers, creeks and mudflats, create a habitat suitable for a diverse array of halophytic plant species and aquatic life. Its elevation, usually under 3 metres above sea level, renders it particularly sensitive to sea-level rise and storm surges – [4].

It's also a UNESCO World Heritage Site and a Biosphere Reserve, given its ecological significance and global conservation value. The Indian part was inscribed on the UNESCO list in 1987 and designated a biosphere reserve in 1989. These designations recognize the role of the region in biodiversity persistence, climate regulation, and coastal protection, and stress the importance of sustainable coexistence of native human populations and the natural ecosystem [6].

1.2 Species Diversity

The forest harbor a high diversity of true mangrove species, and once Heritiera fomes —the namesake "Sundari" tree— was dominant. Other common species are Avicennia marina, Excoecariaagallocha, Ceriopsdecandra, Bruguieragymnorrhiza and Rhizophora mucronata. These species have developed unique physiological and morphological adaptations (e.g., vivipary, salt-excreting leaves, and stilt or pneumatophoric roots) that allow them to survive and prosper at highly saline and anaerobic soils [1].

Sundarbans have rich algal diversity apart from woody vegetation. Saxena and Ajgaonkar (2018): Detailed morphotaxonomic study while recording >30 taxa of green algae including epiphytic and epixylic green algae over mangrove pneumatophores and roots. Genera like Rhizoclonium, Cladophora, and Spirogyra were especially abundant, displaying patterns of seasonal and salinity based distribution. These algae are key players in nutrient cycling, primary production, and microhabitat formation in the mangrove ecosystem [5].

The Indian Sundarbans is also well known for its fauna and is home to the Royal Bengal Tiger (Panthera tigris), an apex predator and the enchantment of this wilderness. The forest also provides habitat for estuarine crocodiles, Irrawaddy and Ganges River dolphins, spotted deer, wild boars and hundreds of bird species, migrant ones among them such as the Asian openbill and lesser adjutant stork. It also acts as a breeding and nursery habitat for a number of crustaceans and finfish, and has a high input to local fisheries [7].

1.3 Ecosystem Services

These mangrove forests provide a multitude of ecological and socio-economic ecosystem services. One of the most important functions they serve is as a natural barrier against cyclones and tidal surges, absorbing wave energy and shielding communities further inland. For instance, cyclones like Aila diminished the effects of storms on human settlements by using the mangrove barrier to a great length [3].

In addition, mangroves of the Sundarbans also act as effective carbon sinks, sequestering substantial amount of organic carbon in their biomass and in the organics-rich soils. They help in the cycling of nutrients, trapping of sediment and stabilization of shorelines, thus preserving the productivity of adjacent coastal and marine ecosystems. From an economic perspective, they sustain traditional ways of life via fisheries, honey harvesting, timber, and non-timber commodities—services that are still crucial for millions living in proximity to the forest margins [8].

2. Environmental Change, Stressors, and Anthropogenic Impacts

2.1 Historical Changes and Forest Dynamics

Over the last century, anthropogenic perturbation and natural changes in ecological regimes have led to pervasive changes in the ecological structure of Sundarban mangrove forest (Asha, 2017). Quantitative forest inventory analyses from 1926 to 1997 showed significant declines in the dominance of major species like Heritiera fomes, while at the same time, expansion of salt-tolerant species such as Excoecariaagallocha. This transition suggests an adaptive ecological response to elevated salinity stress and perhaps selective logging of valuable timber species such as H. fomes [9].

Extensive land reclamation activities during the colonial period cleared and embanked large tracts of forest for rice cultivation, which also enabled settlement expansion. This historic deforestation has had permanent consequences, not only with reduced forest area but also hydrological connectivity and soil salinity regimes. Even in recent decades, such modified land uses, combined with continued subsidence and sea level rise, have been implicated in forest health decline, loss of dense canopy, and the emergence of degraded or bare saline patches [2].

2.2 Shoreline Change and Sea-Level Rise

The Indian Sundarbans, consisting of low-lying estuarine islands including Sagar, Namkhana-Bakkhali and Lothian, are particularly vulnerable to sedimentation, shoreline erosion and changes in sea level. A multi-decadal remote sensing analysis between 1975 and 2017 indicated that erosion consistently outweighed accretion across these islands. The analysis of NDVI trends combined with DSAS, revealed decrease in vegetation loss and biomass in the proximity of hotspot areas of erosion. The geomorphological alterations have not merely diminished the area of land suitable for habitation; they have also resulted in habitat fragmentation and edge effects across the mangrove environment [14].

Additionally, the NDVI time series analysis revealed the presence of significant negative trends along coastline affected by erosion. The vegetation index showed a decreasing Chlorophyll content in forest patches near the shore, especially in areas of hydrodynamic instability where mangroves could not regenerate. Although accretion and re-vegetation were noted in some southern and eastern parts, the overall balance was negative with a total loss of land and vegetation exceeding gains over the 4 decades [10].

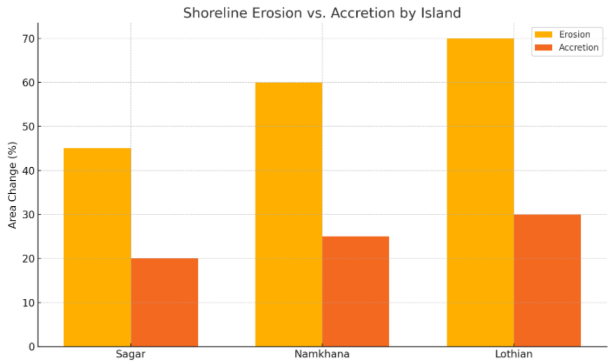

Figure 1: Shoreline Erosion vs. Accretion by Island [14]

2.3 Saltwater Infiltration and Hydrological Modification

Sundarban structural composition along with salinity intrusion due to less flow by the upstream dams and barrages has also become a one of ana single stressor. Changes in river discharge and seasonal flow gradients, along with diminished monsoonal input, have allowed saline water to penetrate far into the estuarine system. This has therefore tipped the ecological balance towards salt-tolerant species, reducing the representation of more freshwater-dependent flora such as H. fomes, and shifted zonation patterns throughout the delta [11].
Soil and surface water salinisation over time limits recruitment of seedlings and disrupts microbial and faunal communities. The wealth of freshwater fish and invertebrate species has fluctuated, causing declines or migrations of local species and fisheries. Freshwater flushing is also inadequate during the dry months, which has permitted salt crystals to form at the surface of the soil, preventing aeration and causing increased losses due to evapotranspiration. Such changes have rendered the forest ecosystem increasingly fragile, with poorer capacity to respond to shocks from outside [13].

2.4 Pressures From Climate and Pollution

The Sundarban ecosystem is situated in a cyclone-prone region that has witnessed a sequence of high-intensity storms in the last two decades, including Cyclone Aila and Amphan. These incidences have caused tree death, defoliation and uprooting, with greater effect in less dense forest patches. When combined with storm surges and saline water inundation, these climatic phenomena have induced long-term physiological stress on mangrove species, resulting in loss of canopy cover and basal area [12].
The stress burden is compounded by climatic threats and pollution resulting from upstream urbanization, aquaculture effluents, and industrial discharges. The nutrient loading and eutrophication trends have been documented in several estuarine channels, which has favoured the growth of specific indicator algal species. Those algal blooms, in turn, change oxygen dynamics and compete with mangrove seedlings for nutrients and space. High concentrations of nitrate and phosphate have been associated with changes in species composition and degradation of previously dense forest areas [1].

3. Monitoring Mangrove Changes: Remote Sensing and Field Approaches

3.1 Spatiotemporal Forest Cover Dynamics (1986–2019)

Use of remote sensing technologies has been pivotal in capturing the spatio-temporal dynamics of mangrove forest cover in the Indian Sundarbans. Satellite-based evaluations based on Landsat imagery and vegetation indices (for example NDVI) between 1986 and 2019 indicated a slow but steady decrease in dense mangrove patches. Over a period of 33 years, nearly 5% of the dense forest cover was lost, most degradation occurring in the southern and southwestern fringes where erosional pressure and salinity ingress were more pronounced [11].
It was also found that dense forest was transformed into degraded forest, and finally, saline blanks or mudflats. This represents a progressive fragmentation and deterioration of the structural integrity of the forest. While a few areas have witnessed afforestation, particularly in the northern zones and emergent char lands, such progress has not been enough to counterbalance the hydroclimatic and anthropogenic drivers of loss [12].

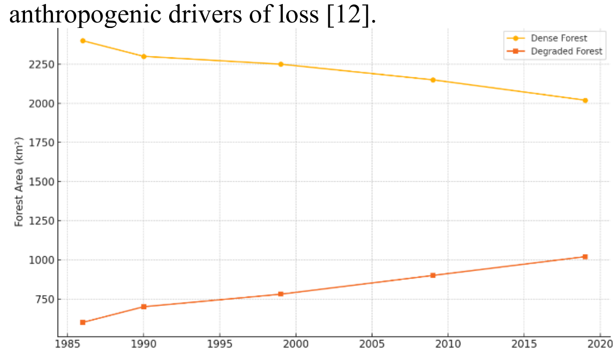

Figure 2: Forest Cover Change in Indian Sundarbans (1986–2019)[11]

3.2 Zonation and Species Classification Using Remote Sensing

Remote sensing technologies, especially those involving hyperspectral and multispectral imagery, have facilitated

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more refined ecological zonation and species-level classification of the Sundarbans. By taking advantage of subtle spectral differences, differences between specific mangrove species and vegetation types were distinguished using EO-1 Hyperion hyperspectral data. This enabled greater precision in the mapping of true mangroves vs associate vegetation, and identification of specific species, e.g. Avicennia, Excoecaria, and Heritiera over different ranges of salinity and tidal zones [9].

As a result of applying high-resolution imagery with advanced classification algorithms including Support Vector Machines (SVM) and Random Forest to our data, we are starting to understand how these species are distributed in relation to not only hydrological connectivity but also salinity gradients. Thus, these techniques have been particularly effective at identifying regeneration zones, degraded patches, and newly colonized mudflats—critical information for conservation efforts and zonal management [13].

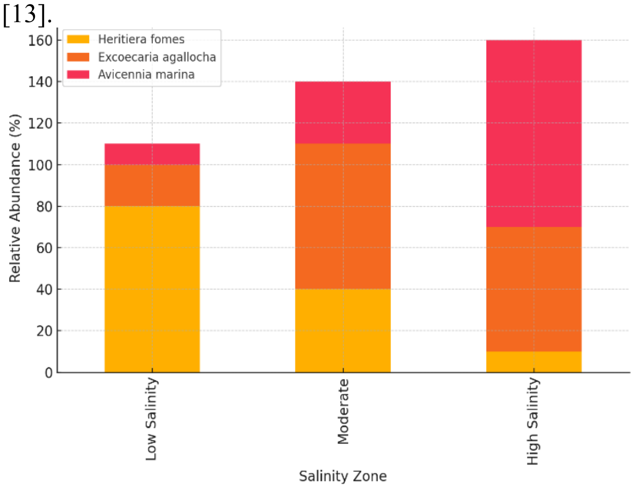

Figure 3: Species Zonation Across Salinity Gradient [9]

3.3 Time Series of NDVI and Vegetation Health

The NDVI-based time series analysis has proved to be a utility for assessing vegetation health over the Sundarbans. Lower NDVI values have been distinctly associated with shoreline erosion zones characterized by frequent tidal inundation and saline stress that limits photosynthetic activity. A 30-year time-series data revealed that areas adjacent to tidal creeks and the Bay of Bengal had the sharpest decrease in NDVI, representing physiological stress and depletion in vegetative vigor [14].

In contrast, some accreting zones located in the eastern Sundarbans showed stable or even increasing trends of NDVI pointing the regeneration and successful mangrove colonization process in the eastern Sundarbans. Using these NDVI patterns, field validation, and complementary data we can devise predictive models of areas of vulnerability and potential sites of restoration. Therefore, the combination of NDVI analysis with elevation, slope, and tidal information represents a readily deployable, cost-effective, and scalable solution for forest health monitoring and adaptive management [13]

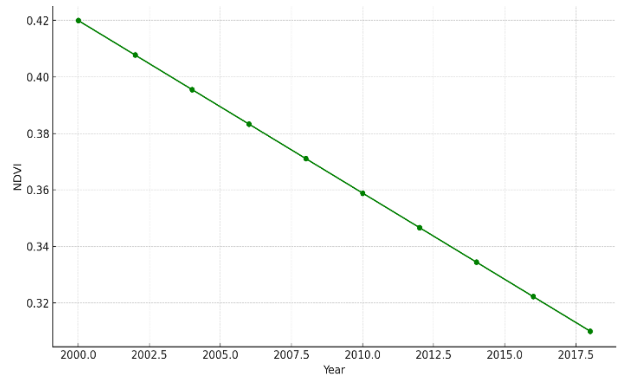

Figure 4: NDVI Trend in Erosion Zones (2000–2020) [14]

4. Conservation Strategies, Management Challenges, and Future Directions

4.1 Existing frameworks and policies

The Indian Sundarbans, as a World Heritage Site and a Biosphere Reserve, has received considerable level of recognition in national as well as international conservation agenda. The adoption of conservation mandates into the law on the ground has been difficult, though. While the formal legislative backbone for India's natural resource planning and management already exists in the form of India's Forest Conservation Act and CRZ notifications, y enforcement has often been sporadic and unscientific, owing to institutional overlap and diversity in available human and financial resources that is constrained by socio-political pressures from resource-dependent communities [14].

The forest also has potential under international carbon-offset mechanisms such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation). Due to the globally significant carbon sequestration potential, as well as its increased annual climate vulnerability, harmonizing local conservation efforts with international climate financing instruments could unlock both nature and economic benefits for the region. Nevertheless, this would only be doable with systematic capacity-building, baseline carbon assessments and transparent benefit-sharing mechanisms to make sure of local participation and equity [14].

4.2. Community and Scientific Approaches

While the limits of solely top-down or government-led conservation models are increasingly recognized, community-based forest management (CBFM) and participatory restoration are garnering more and more attention. Joint Forest Management Committees (JFMCs) have also been started in some of the regions, though most of them lack appropriate financial support as well as legal empowerment. Where they have proven successful, such partnerships have supported ecotourism projects, honey cooperatives and sustainable aquaculture — presenting alternatives to resource extraction [2].
It has to be noted that NGOs have been instrumental in linking scientific knowledge with grassroot implementation. With awareness-raising campaigns, ecological restoration projects and microcredit assistance, these agencies have engaged local populations in forest stewardship. Informed by salinity and hydrological zoning, successful pilot projects demonstrate the ability to restore mangroves on accreting mudflats and saline blanks with native species [14].

4.3 A Sustainable Future: Recommendations

A multidimensional strategy comprising an ecological integrity driven and a socially resilient approach is the pathway towards tenure for the Indian Sundarbans. The top recommendations include increasing freshwater flow via upstream policy changes, encouraging sediment delivery to promote natural land building processes, and zoning restrictions on destructive land use near vulnerable margins [13].
Climate adaptation needs to be integrated into local and regional planning. This means developing cyclone-resilient infrastructure and promoting climate-smart agriculture and preserving natural buffers, such as mangroves and tidal wetlands. This community participation associated with remote sensing-based forest health monitoring can provide near real-time forest health data that would allow faster response and adaptive management. In the Sundarbans complex socio-ecological space, initiatives that integrate scientific innovation with traditional knowledge will be critical [14].

5. Conclusion

The Indian Sundarban mangrove forest, a globally significant ecological system, embodies the complex interplay between biodiversity, environmental dynamics, and human dependency. As this review highlights, the forest has undergone considerable structural and functional transformations driven by both natural processes and anthropogenic pressures. Historical deforestation, altered hydrology, salinity intrusion, and shoreline erosion have eroded ecosystem resilience, while recent advances in remote sensing have greatly improved our ability to monitor and assess forest health in real time.
Despite these challenges, there remains cautious optimism. Evidence from zonation studies, NDVI trends, and community-led restoration programs demonstrates that targeted, science-backed interventions can reverse degradation patterns in specific areas. The integration of policy mechanisms like REDD+, participatory management, and spatially explicit conservation planning offers a pathway to a more sustainable and resilient future for this ecosystem.
To safeguard the Sundarbans, a shift from reactive to proactive governance is essential—one that empowers local communities, strengthens institutional coordination, and aligns conservation goals with climate adaptation strategies. The forest's future will depend not only on technological solutions but also on inclusive frameworks that recognize the socio-ecological fabric unique to this deltaic region.

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