

Chapter 24

Mangroves in Cyclone-Battered Sundarbans, India: A Geoinformatics-Based Multi-temporal Study



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24.1 Introduction

Forest damages caused by notorious cyclones (1988, 2007, 2009, 2019, and 2020) of the previous decades have exposed the capacity and inability of the mangrove buffers in the Indian Sundarbans. The buffer width varies from 149 km (SE) to only 30 km (SW) in the coastal fringe forests and is separated by the larger tidal river mouths of Ichhamati-Raimangal, Gosaba, Matla, Thakuran, and Saptamukhi in the physiographic settings (deltaic and estuarine) of the Indian Sundarbans. Mature mangroves were distributed on the seafront island shores, inner deltaic platforms, and the levee surfaces of the tidal channels of the coastal settings and inland deltaic settings (Paul, 2002). Other areas are occupied by younger mangroves, stunted mangroves, and saltmarsh vegetation in the lower part of the Ganga delta. The thicker and more compact mud banks, nutrient-rich muds, and active tidal flats with saltwater inundations harbour the quality mangroves. Rapid aggradation,

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autocompaction of tidal sediments, freshwater mixing or brackish water quality, and stability of the substrate alluviums support ideal environmental gradients for holding the mangrove regeneration processes in the deltaic islands.

Using the satellite data (Landsat 4 and 5, 7 and 8), the areal coverage index, Normalised Differential Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI) are assessed for mangrove forests in the region in pre- and post-storm situations to identify the nature of cyclone-battered mangrove forests in the Indian Sundarbans. The damage types are observed in the islands during and after the occurrences of a few cyclones (e.g., Aila, Bulbul, and Amphan) in the Indian Sundarbans. In the field of surveying and monitoring vegetation, they are identified as (i) loss of mangroves by erosion, (ii) top breakage of mangrove trees by wind storms, (iii) overwash sand lobes encroachments and forest damages, (iv) loss of soil nutrients by removal of top soils, (v) burnt-out trees by salt sprays and moisture sucking effects, (vi) dieback of mangroves by salt encrustation of pan surface clay beds, and (vii) damages due to twisting of trees by strong wind speed. Observations also show that 45% of mangroves in the Indian Sundarbans were damaged by the multiple effects of cyclones. The habitat restoration of mangroves with green solution management through repeated plantations of mangrove saplings in the favourable tidal flats, regular monitoring of the plantation sites, and participation of the locals in the management process will extend the composition of mangrove buffers in the Indian Sundarbans and reduce the damages caused by cyclones.

Mangroves of the Indian Sundarbans are also studied on different aspects of environmental issues as cyclonic impacts (Paul, 2000b, 2002; Ghosh & Naskar, 2012); forest types and quality (Paul, 1996a; Hati et al., 2021; Mondal & Paul, 2022); ecological diversity of mangrove forests (Choudhury et al., 1984; Ghosh et al., 2015; Ray et al., 2014); climate change impacts on the mangrove forest in the Indian Sundarbans (Paul, 1996b; Raha, 2014; Chakraborty et al., 2014; Paul & Paul, 2022); and physiographic diversity of Indian Sundarbans with vegetation characteristics (Paul & Bandyopadhyay, 1985, 1988; Paul, 2000a, 2014, 2022; Majumdar et al., 2012) by the different researchers.

24.2 Materials and Methods

The cyclone-battered Sundarbans are studied using geoinformatics for identification of forest damages to highlight the nature of changes in the isolated forest patches of Lothian Island and Dhanchi Island units in the Saptamukhi estuary and Thakuran estuary. Landsat data series (2000, 2010, 2015, and 2021) of the Sundarban deltaic islands, field monitoring after the storms, and other aspect data related to cyclone damages are used to carry out the research in the Indian Sundarbans. The spectral index of satellite data is analysed in software tools for recording the changes in forest resources after each storm in the Sundarbans. Final output maps of

classification images, vegetation index calculation, and leaf area concentration zones during and after the events of the storm will highlight the types of forest damages in the study areas.

Based on K-Means clustering unsupervised classification algorithm the mangrove forests of Lothian and Dhanchi Island are classified for assessment of temporal changes from 2000 to 2021. However, the EVI, NDVI, and LAI are calculated for the island forests to estimate the leaf morphology and health conditions under the impacts of cyclonic storms. The following Eqs. 24.1, 24.2, and 24.3 (Rouse et al., 1974; Green et al., 1997; Huete et al., 2002) are used in calculation to express the above parameters:

$$\text{EVI} = G \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + C_1 \times \text{Red} - C_2 \times \text{Blue} + L)} \quad (24.1)$$

where, L refers to the canopy background adjustment for correcting the nonlinear matrix function, differential NIR, and red radiant transfer through a canopy; C_1 and C_2 refer to the coefficients of the aerosol resistance term (the blue band to correct for aerosol influences in the red band); and G is a gain or scaling factor. The coefficients adopted for the MODIS EVI algorithm are $L = 1$, $C_1 = 6$, $C_2 = 7.5$, and $G = 2.5$:

$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \quad (24.2)$$

$$\text{LAI} = 12.74 \times \text{NDVI} + 1.34 \quad (24.3)$$

24.3 Study Area

Indian Sundarbans harbour diverse character of mangroves, which are distributed in south-eastern zones, estuarine complexes, and southwestern zones in between Saptamukhi River and Ichhamati-Raimangal River. However, the study is conducted at the local level, particularly in Lothian Island and Dhanchi Island of the Indian Sundarbans. Storm damage plays a significant role in successional modification in mangroves. Being located in the mouth of the Saptamukhi tidal estuary, the Lothian Island represents the signatures of storm surges and tidal surges in the south western Sundarbans. Dhanchi Island, on the other hand, bears multiple effects of cyclonic storms along the Thakuran River estuary reaches in the middle part of the Indian Sundarbans (Fig. 24.1).

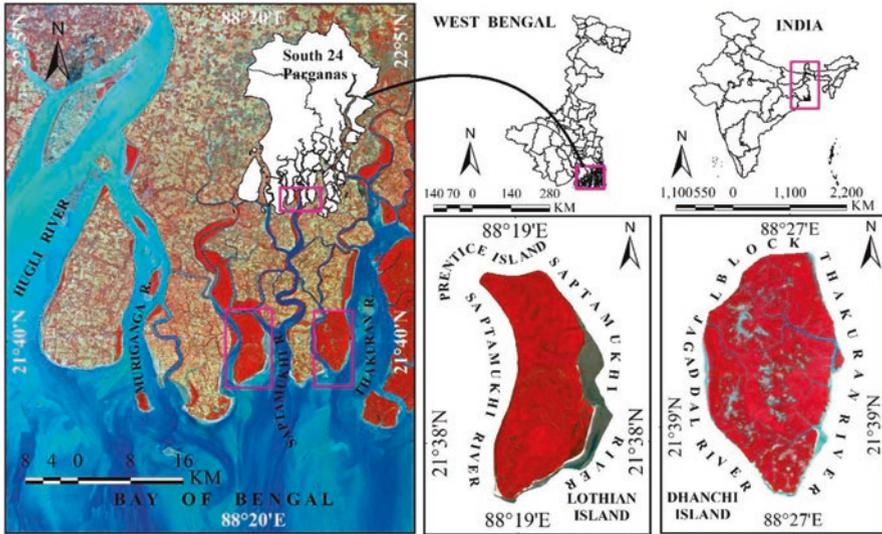


Fig. 24.1 Southwestern part of Indian Sundarbans with estuarine location of Lothian and Dhanchi Island

24.4 Results and Discussion

The section will demonstrate the declining trend of mangroves on Lothian Island and Dhanchi Island in multiple ways of impacts on the cyclone batter environment. The cyclonic wind velocities, wind-driven wave steepness, associated longshore currents, wind-driven tidal surges, storm surges, and saltwater inundations played an important role in the modifications of mangroves during the previous cyclones (1988, 1995, 2007, 2009, 2020, and 2021). Mangrove losses resulting from erosion of the island banks, shifting sands by washover deposits, hypersalinities, and storm damage to trees are discussed using geoinformatics and field surveys (Fig. 24.2).

24.4.1 Storm Induce Land Erosion

Changing configurations of the island shorelines and tidal channel banks due to land erosion have reduced the areal coverage of mangroves on Lothian Island and Dhanchi Island (Figs. 24.2 and 24.3). Mangrove-dominated island banks on the sea face are affected by the removal of top soil and sheet erosion due to breaking waves and longshore current energies concentrated in the forest fringe landscapes. Tidal surges driven by strong wind speed along the estuary banks and other tidal river banks undermined the bank margin soils and removed the trees with collapsing banks after the storms. About 1.77 km² area of forest lands are eroded in Lothian



Fig. 24.2 Mangrove Forest of Dhanchi and Lothian Island: Levee forest along the tidal creeks, shoreline mangroves damaged by the cyclonic storms, channel bank mangroves affected by erosion in the storms, and tidal swampy forest

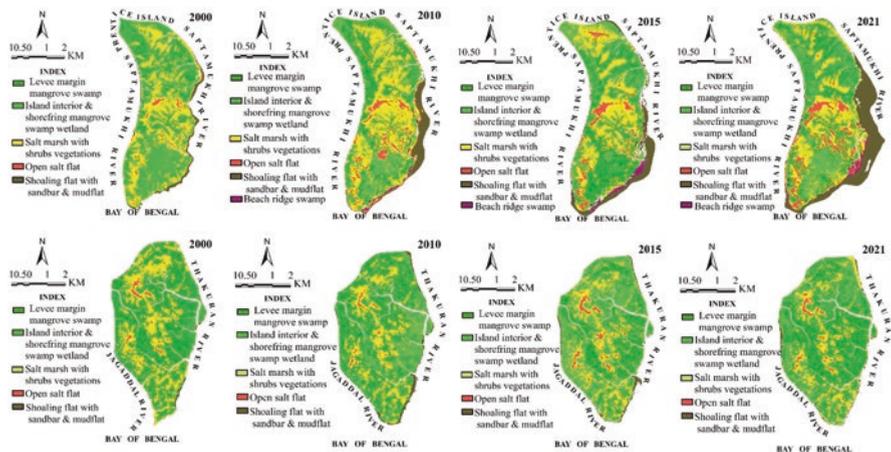


Fig. 24.3 Classification of mangrove ecosystem diversity on a temporal scale from 2000 to 2021 using the Landsat imagery for Lothian and Dhanchi island in the Indian Sundarbans

Island, and 2.55 km² of forest lands are eroded in Dhanchi Island, between 2005 and 2022, when maximum impacts were registered during the events of cyclones. The mangrove coverage area is reduced to 1.55 km², particularly due to erosion between

2006 and 2022, though afforestation was introduced after ‘Aila’ cyclone (2009) in the region.

The mangrove forest of Dhanchi and Lothian Island are classified on the Landsat images from 2000 to 2021 to identify the different categories of mangrove ecosystems and their dynamics (Figs. 24.3 and 24.4, Table 24.1). The study represents loss

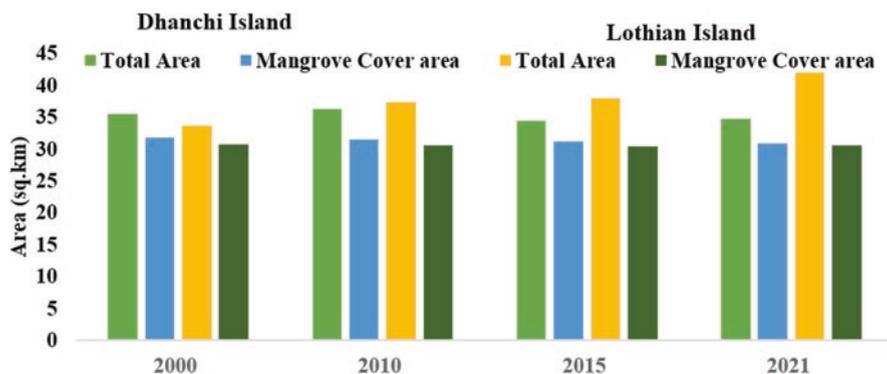


Fig. 24.4 Changing coverage of mangrove forest area in Dhanchi and Lothian Island

Table 24.1 The classification of mangrove habitat types and their changes during 2000, 2010, 2015, and 2021 for the Lothian and Dhanchi Islands

Sl. No.	Mangrove Habitats	Area in 2000 (sq. km)	Area in 2010 (sq. km)	Area in 2015 (sq. km)	Area in 2021 (sq. km)
Mangrove Zonation in Lothian					
1	Beach ridge swamp	0	0.29	0.73	0.57
2	Island Interior and Shorefring Mangrove Swamp Wetland	13.21	5.82	6.24	7.78
3	Levee margin mangrove swamp	6.24	10.15	12.70	11.54
4	Open Salt Flat	0.79	2.70	2.62	3.81
5	Salt marsh with shrubs vegetations	11.27	14.35	10.79	10.69
6	Shoaling flat with sandbar and mudflat	1.16	2.43	2.89	6.78
7	Tidal creeks and waterbody	1.03	1.59	1.92	0.82
Mangrove Zonation in Dhanchi					
1	Island Interior and Shorefring Mangrove Swamp Wetland	1.80	8.10	12.47	6.18
2	Levee margin mangrove swamp	19.24	15.33	10.60	17.48
3	Open Salt Flat	0.59	0.43	1.09	0.75
4	Salt marsh with shrubs vegetations	10.69	7.98	8.05	7.24
5	Shoaling flat with sandbar and mudflat	0.28	1.005	0.73	0.52
6	Tidal creeks and waterbody	2.83	3.43	1.52	2.56



Fig. 24.5 Loss of shore fringe mangrove forests due to (a) transgressive sand sheets and (b) wind damages with the signatures of relict forest or submerged forest at the sea front positions resultant from the impacts of cyclones

of the mangrove vegetations over the temporal scale in the region of the Indian Sundarbans resulting from cyclone batterer environment and storminess of the sea

24.4.2 *Shifting Sands by Washover Deposits*

The narrow shoreline beaches and low-height beach ridges of these islands were unable to hold the storm surges of cyclones ‘Aila’ and ‘Amphan’, thus sediment-laden waters encroached into the forest belts by advancing overwashed sands. Mangroves were trapped by such overwash sand deposits after the cyclone Amphan. A large tract of sand shoals was extended towards the south-eastern fringe forest in Lothian Island after the events of previous cyclones (Fig. 24.5). Tidal surges driven by winds during ‘Yass’ cyclone (2021) pushed the sands into the forests through overwashed sand fan lobes in the modification of mangroves. Southern parts of Dhanchi Island were also affected similarly by mangrove damage from shifting sands.

24.4.3 *Hypersalinities*

The storm surge sea waters inundated the low-lying surface pans with concave upward-shaped mud banks, and stagnant sea waters held for a long time in the depressions after the landfalls of repeated cyclones in the region of Lothian and Dhanchi islands. As the cyclone passed over the region, the muddy surface of depression basins became encrusted with salts due to evaporation in the region. Such hypersalinities of the surface soils do not allow the mangrove to grow or regenerate the mangrove seeds. The dieback of mangroves is registered at the pan fringes, possibly due to increased soil salinity after evaporation. Thus, a series of salt pan areas emerged in the coastal parts of Lothian and in a large part of Dhanchi

Island. Thus, the gradual development of saline blanks has reduced mangroves in the Sundarbans.

24.4.4 Storm Damages to the Mangrove Trees

The types of damage to mangroves are observed in the Sundarbans during the field visits for monitoring forest status after the events of the Aila cyclone (2009) and the Amphan cyclone (2020). Storm surge elevations of the notorious cyclones were registered at 3.5–4.0 m (2009) above the ground level in the south-eastern parts of the Indian Sundarbans around the Malta–Raimangal–Ichhamati complex (Gayathri et al., 2015). Similarly, the elevation of the surge level was registered as 2.5–3.5 m on the shorelines fringed with mangroves in the western part of the Indian Sundarbans during the landfall of tropical cyclone ‘Amphan’ in 2020 (INCOIS, 2020), around the Matla-Hugli estuarine complex. Such devastating surge heights produced bank erosion, bank instability, and overwash encroachments with external inputs of sand over the forest fringe environment (Paul et al., 2017, 2018) in parts of the Indian Sundarbans. Chunks of the forest fringe lands were collapsed with uprooted trees along the tidal river banks after undermining the valley sides with strong currents generated in the surge waters in the cyclone-affected region. Wood logs of the mature mangrove trees were degraded by saltwater inundations and aggradations of sediments along the river banks after the events of cyclones, and many logs were also drifted into the downstream with the energy levels of return currents. However, on the sea face along the shore fringe mangroves, removal of top soils and overwash sand deposits destroyed mature mangrove trees after the events of tropical cyclone landfalls in the region. Mangrove loss is also documented from the emerging salt pans within the forest lands after they hold the surge waters into the surface depressions. Gradually, with the evaporation process, the clay beds were encrusted with salt crystals and destroyed mangroves by ‘die-back’ processes in the emerging hypersaline patches or saline blanks within the forest lands as a result of surge water penetration into the island interiors of the Sundarbans (Paul et al., 2018) during the cyclones (Fig. 24.5).

Trees lined with top breakages along the sea face represent the impact of wind storms in Dhanchi Island and Lothian Island of the southwestern shorelines in the Sundarbans between the Saptamukhi and Thakuran complexes. As they are damaged on the island platform surface, the basement layer of swamp clays has been removed by surface etching during storm water level currents and wave abrasion processes in the region. Thus, emerging stiff clay beds in unfavourable conditions do not support the mangrove regeneration process along the unstable shorelines by anchoring the viviparous mangrove seeds that drift on the sea face during storms. Mature mangrove trees were also twisted, uprooted, bended, and burned alive during strong wind velocity, salt sprays, and prevailing dry winds in the vicinity of the

wall of circular movement of cyclonic winds after the landfall in the forest fringe environment. Using geoinformatics in the study, we demonstrate the Normalised Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI) values that indicate the status of mangrove forests spatially and temporarily after and before the events of tropical cyclone landfalls in the Sundarbans (Figs. 24.6 and 24.7). Such degraded areas of forests are reflected in the LAI output maps of the two islands under study. The study highlights the reduction of NDVI, EVI, and LAI values for the cases of Lothian and Dhanchi islands in a temporal scale from 2000 to 2021. In Lothian Island the NDVI was 1.0 in 2000 and it is reduced to 0.96 in 2021; EVI on the other hand, showed 0.64 in 2000 and it is reduced to 0.57 in 2021; and LAI is also reduced to 13.48 in 2021 from 14.08 in 2000. Similarly, in Dhanchi island the NDVI showing reduction of 0.96 from 0.98, EVI showing a slight increase of 0.69 from 0.63 over the temporal scale, and the LAI is significantly reduced into 13.65 from 13.74 due to the impact of cyclonic storms by this time period (Figs. 24.6 and 24.7).

24.4.5 Climate Change Reworking and Forest Management

Climate change acceleration with sea level rise and storminess of the sea affected the deltaic islands of the Indian Sundarbans by reworking coastal landscapes with marine influences (Paul, 1996b; Paul & Paul, 2022; Raha, 2014; Chakraborty et al., 2014). The rate of aggradation and the rate of progradation of the islands were balanced by the supply and accumulation of sediments as well as the uninterrupted continuation of natural mangrove regeneration processes on the island platforms (Table 24.2 and Fig. 24.8). As the energy levels, anthropogenic controlled discharges of the river basin, and marine impacts have changed, the equilibrium is affected in sedimentation, and the reworking of landscapes further aggravates the situation of mangrove habitats in the Indian Sundarbans.

Attempts have been made to restore the vibrating ecosystem through different approaches to forest management. They are identified as (i) ecological engineering methods; (ii) mangrove afforestation for wild life conservation; (iii) improving ecological buffers in the biosphere reserve; and (iv) emerging concepts of the environmental value of the landscapes. Habitat restoration and carbon sequestration are other functions of mangrove forests currently realised by environmentalists, researchers, locals, and coastal managers in the region for managing the mangrove buffers. To minimise the impacts of cyclones and the coastal squeeze in the Sundarbans, people are involving themselves in the mangrove afforestation programmes.

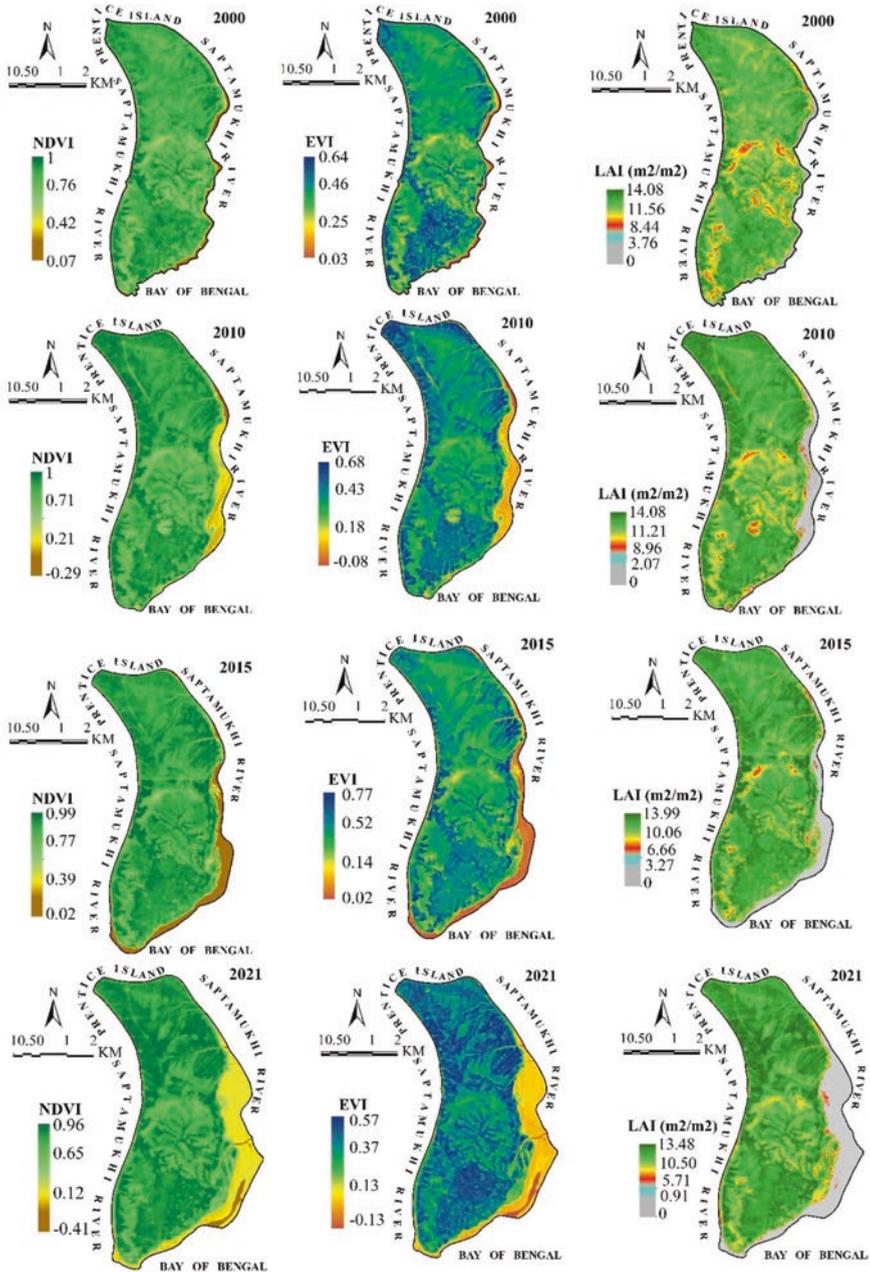


Fig. 24.6 Estimated spectral indices signature for NDVI, EVI, and LAI in Lothian island of Indian Sundarbans from 2000 to 2021

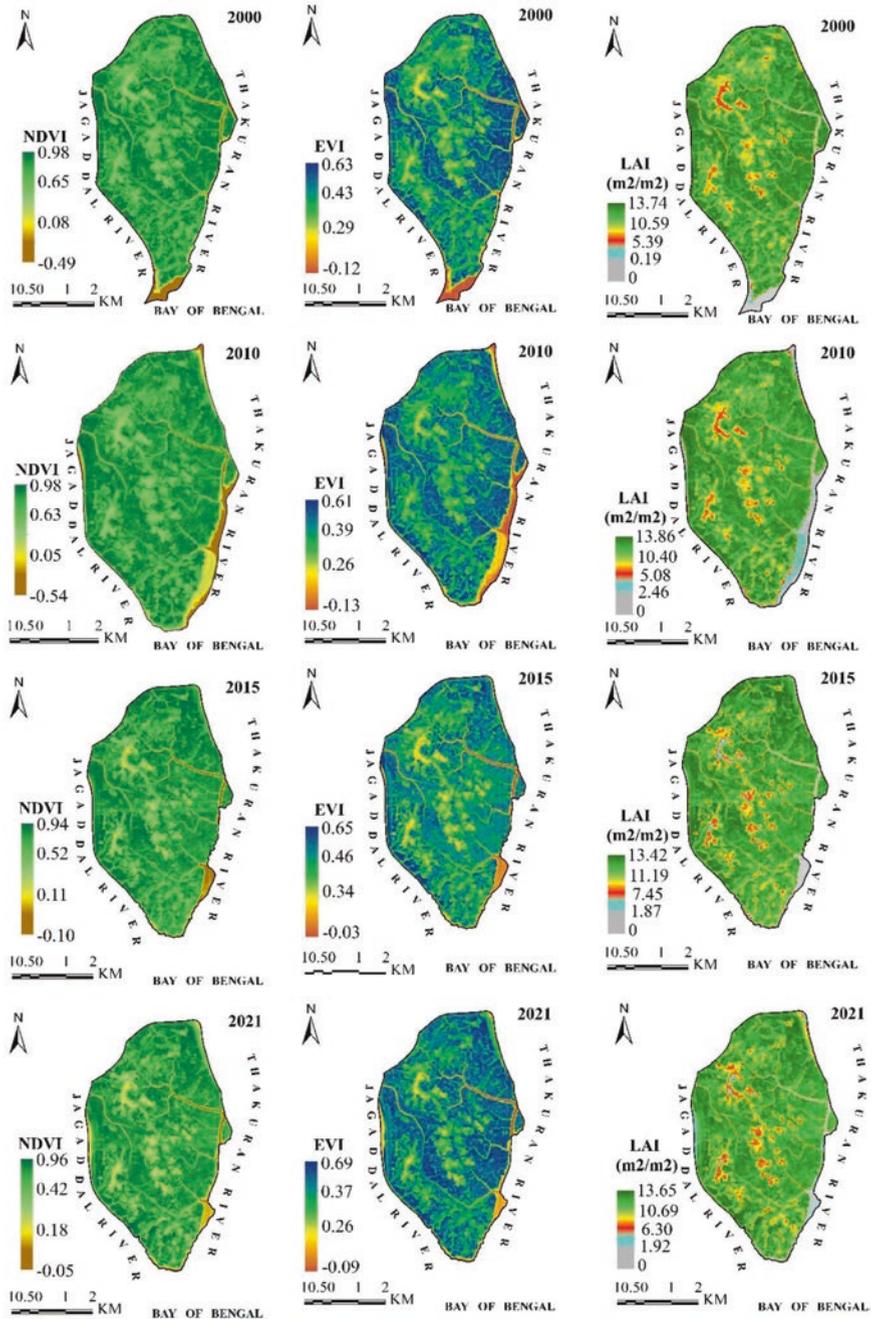


Fig. 24.7 Estimated spectral indices signature for NDVI, EVI, and LAI in Dhanchi island of Indian Sundarbans from 2000 to 2021

Table 24.2 The structure of forest habitats in physiographic settings and their degradation levels as a result of cyclonic storms in the previous decades along with the impacts of climate change reworking of the landscapes of estuarine setting in the Indian Sundarbans

Physiographic Settings	Forest Quality	Sedimentary Environment (Sediment Input and Output)	Tidal Environment (Inundation Frequency)	Water Quality in Pre-monsoon (Water Salinity in PPT)	Energy Levels
Fringe forest of the shorelines along the tidal rivers	Dynamic forest	Ag + Pg + Rg	Frequent	16–17	Tidal currents and tidal surges
Adjoining forest of the salt pans	Dwarfed forest	Dg	Low	25–28	Ponded water
Levee forest along the creeks	Living forest	Pg + Ag	High	17–18	Tidal flood current
Tidal swamp forest in the low gradient flats	Living forest	Ag	High	18–19	Tidal flood current
Littoral fringe forest	Buffer forest	Tg	Moderate	20–21	Storm surges
Relict forest along the seashores	Dead forest	Rg	Frequent	>21	Storms, winds, waves, longshore currents

Key: *Ag* Aggradation, *Pg* Progradation, *Dg* Degradation, *Tg* Transgressive sands, *Rg* Retrogradation

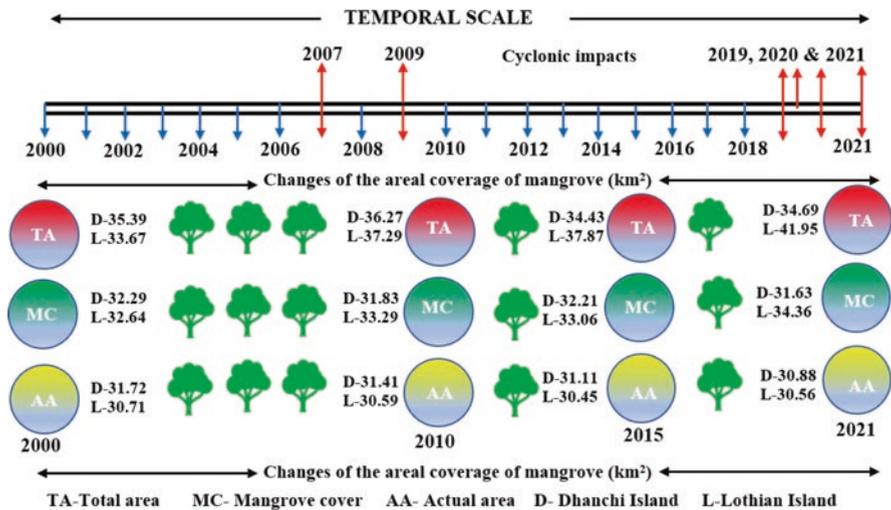


Fig. 24.8 Hammering effects of cyclone landfalls in the Sundarbans and the temporal changes of mangrove cover area as well as the rate of reduction of the forest estimated using remote sensing techniques

24.5 Conclusion

The Indian part of the Sundarbans was battered by eight notorious cyclones from 1988 to 2021 at an average recurrence interval of 4 years, which destroyed the mangrove forests in the coastal fringes. Climate change reworking with high rates of event frequencies from cyclones and sea level rise impacts has demonstrated the significant loss of mangroves in the Indian Sundarbans. The forest cover area changes for Lothian Island and Dhanchi Island represent spatiotemporal variations using image classification (Landsat 8 OLI) of satellite data (2000 to 2021) to detect the sites of degradation. Post-cyclone damages to the forest resources are also identified with the use of Leaf Area Index (LAI) values calculated for the study areas in the present work. The estimated values of NDVI, EVI, and LAI for the Lothian and Dhanchi island represent significant loss of vegetations and quality of vegetations along the shore fringes, channel banks, salt pans, and the littoral tracts. In Dhanchi island the LAI values are significantly reduced from 13.74 (2000) to 13.65 (2021). Similarly, the LAI is also reduced from 14.08 (2000) to 13.48 (2021) in Lothian Island. This measurement indicates the loss of forest quality in estuarine islands at the shore face and channel banks in the Indian Sundarbans under cyclone batter environment.

Cyclonic storms played a significant role in the zonation and plant succession of mangroves over a long time in the Sundarbans. Island interior zoned species have been exposed along the tidal river banks as a result of channel shifting caused by erosion and the loss of primary mangroves from the eroded mud banks after the events of cyclones. Signatures of relict forests are visible along the shore fringe forests, where exposures of vertical tree stumps with older pneumatophores are found on the erosive mud banks of the Bay of Bengal fringe islands. Storm-damaged trees are also found above the high tide line on Dhanchi Island of the Thakuran-Matla Estuarine Complex. Expansion of salt pans or saline blanks in the interior parts of the islands indicates the damages to the forest stands due to emerging hypersalinity. Salt flats and salt marshes represent stunted or dwarfed vegetation on the salt-affected surface in the inner parts of the islands. The immediate effects of cyclonic storms are seen in the forest fringe environment, with the signatures of partially damaged trees in the southwestern Sundarbans. Application of geoinformatics in the generation of databases will provide information for forest management in the deltaic islands. Ecological engineering methods, such as constructing drainage ditches to connect the tidal rivers for supply of moisture, can restore forests in favourable conditions, but mangrove afforestation in the degradation sites will restore habitats with monitoring the status of planted trees in the Sundarbans.

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