

Cyclone Impacts on Mangrove Resilience in the Sundarbans: A Satellite-Based Multi-temporal Vegetation Index Approach

Md. Saifur Rahman*, Afrin Akter Akhi, Md. Touhiduzzaman, Mawya Siddeqa

Department of Geoinformation Science and Earth Observation, Faculty of Environmental Science and Disaster Management, Patuakhali Science and Technology University, Patuakhali-8602, Bangladesh

*Correspondence: saifgeo@pstu.ac.bd

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Abstract: The Sundarbans mangrove ecosystem is the world's largest contiguous mangrove forest. It provides vital ecosystem services and high levels of carbon sequestration, as well as protecting the Ganges-Brahmaputra-Meghna Delta from coastal storm surges. However, severe tropical cyclones are increasingly threatening the structural integrity and long-term resilience of this vital ecosystem. This study presents a multitemporal remote sensing framework for quantifying mangrove vegetation degradation and post-cyclone regeneration dynamics in the Sundarbans after Cyclones Aila (2009) and Bulbul (2019). Using Landsat-5 TM and Landsat-8 OLI surface reflectance data, we evaluated two remote sensing vegetation indices, the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), across pre- and post-storm periods. McNemar's chi-square (χ^2) tests and paired t-tests were used to confirm the statistical significance of land-cover transformations and spectral index shifts ($p < 0.001$). Following Cyclone Aila, there was a drastic net decrease in sparse vegetation of 679.81 km² (-88.12%), while dense vegetation increased from 2,803.90 km² to 3,576.21 km². Similarly, following Cyclone Bulbul, sparse vegetation dropped from 303.39 km², to 164.90 km². Meanwhile dense vegetation rose from 3,314.73 km² to 3,469.42 km² giving a gain of 154.69 km². Our EVI analysis shows that shrub and grassland areas suffered damage but dense vegetation zones returned to normal within just 12 months of Cyclone Bulbul and the other cyclone. This rapid stabilisation shows that the Sundarbans mangrove ecosystem is highly resilient. Therefore, implementing ecosystem-based management strategies is essential to keep the Sundarbans mangrove ecosystem healthy in the long-term and to help the Sundarbans mangrove ecosystem adapt to climate change.

Keywords: Sundarbans, vegetation change, cyclone, NDVI, EVI, remote sensing, McNemar test

Introduction

Mangrove forests play an important part in keeping the global carbon cycle in balance. They work well as carbon sinks. Offer essential ecological services. The Sundarbans, which is shared between Bangladesh and India is the continuous mangrove ecosystem in the world. It covers about 6,017 kilometers in Bangladesh. This natural area of mangrove forest helps to protect communities from terrible cyclones and big tides (Gopal & Chauhan 2006; Iftekhar & Saenger 2008). Research has found that mangroves can take in, up to four times carbon than regular tropical rainforests (Donato et al., 2011). However cutting down trees quickly and using land in a way that's not sustainable directly put the mangrove ecosystem at risk. This weakness gets worse because of climate change. Climate change causes the sea level to go up and makes storms stronger (Giri et al., 2011; FAO, 2007). All these problems happen again and again. They put the structure of the mangrove ecosystem in danger. They also put the ability of the mangrove ecosystem to store carbon in danger.

Remote sensing (RS) and Geographic Information System (GIS) technologies are indispensable for monitoring mangrove dynamics, especially in hard-to-reach regions. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI) and Enhanced Vegetation Index (EVI) are widely used to measure the health of vegetation and changes in biomass. While

the NDVI is effective for assessing greenness, the SAVI corrects for soil brightness in areas with low vegetation, and the EVI improves sensitivity in areas with high biomass (Foody et al., 2001; Huete et al., 2002; Li et al., 2007). The Sundarbans have faced multiple severe storms over the years, including Cyclones Sidr (2007), Aila (2009) and Bulbul (2019). Each storm affected the forest differently: for instance, Aila caused widespread damage to shrubs and sparse vegetation, whereas Bulbul removed 10.02 km² of vegetation, severely impacting the southwestern Sundarbans. These impacts demonstrate the importance of continuous monitoring in guiding restoration and climate-resilient management strategies (CEGIS, 2007; Mondal et al., 2022).

Bangladesh's coastal region is one of the area's most prone to cyclones globally. Over the past two decades, the frequency and intensity of cyclones have increased. Experts predict a potential 50% increase in post-monsoon cyclonic activity by the period 2041–2060 (BMD, 2020). These trends pose a direct threat to the ecological and economic stability of the Sundarbans. While past research has thoroughly documented the immediate damage caused by cyclones, we know very little about how mangrove ecosystems regenerate over time. Most previous studies are based on broad vegetation classes using low-to-medium-resolution satellite imagery and thus fail to address species-specific responses and long-term recovery patterns. Furthermore, critical environmental variables such as water salinity, sedimentation and local tidal flow are not monitored, and socio-ecological factors driving these changes are ignored.

This study aims to fill these gaps by looking at how vegetation changed before and after Cyclones Aila and Bulbul using NDVI and EVI, derived from multi-temporal Landsat imagery. This study specifically looks on the spatial and temporal changes of vegetation loss and regeneration across different mangrove classes and evaluates their resilience under repeated cyclonic stress. By doing this, the study helps people understand how mangrove ecosystems react to climate change-induced disturbances and provides evidence to support ecosystem-based management strategies for coastal resilience.

Materials and Methods

Study Area

The study was carried out in the Bangladeshi portion of the Sundarbans, the world's largest halophytic mangrove forest, located in the southwestern coastal region of Bangladesh. Geographically, Sundarbans stretches from latitude 21°30'N to 22°30'N and longitude 89°00'E to 89°55'E (Figure 1). The total land area of the Sundarbans in Bangladesh amounts to about 6,017 km², of which 4,120 km² is dense mangrove forest and 1,897 km² consists of water, such as rivers, creeks, and tidal channels (Islam, 2011).

Geomorphologically, the Sundarbans hold 200 islands fed by a dense network of more than 400 interconnected tidal rivers, channels, and creeks. The land is low-lying, with elevations ranging from 0.9 m to 2.1 m above mean sea level. Sundarbans is dominated by silty clay loam soils subjected to regular flooding due to semi-diurnal tides (Iftekhar & Islam, 2004). The area has a tropical climate characterized by a strong monsoon season that lasts from May to October (Ghosh et al., 2016). Ecologically, the Sundarbans play a critical role in stabilizing coastal ecosystems, conserving biodiversity, and reducing the destructive impacts of tropical cyclones. The forest vegetation is dominated by key mangrove species, including *heritiera fomes* (Sundari), *Excoecaria agallocha* (Gewa), *Sonneratia apetata* (Keora), and *Xylocarpus granatum* (Passur), along with species belonging to *Avicennia* spp. And *Xylocarpus* spp. Due to its exposed geographical location, the study area is highly vulnerable to frequent tropical cyclones. Consequently, the vegetation dynamics in this region are strongly influenced by major cyclonic events, such as Cyclone Sidr (2007), Cyclone Aila (2009), and Cyclone Bulbul (2019).

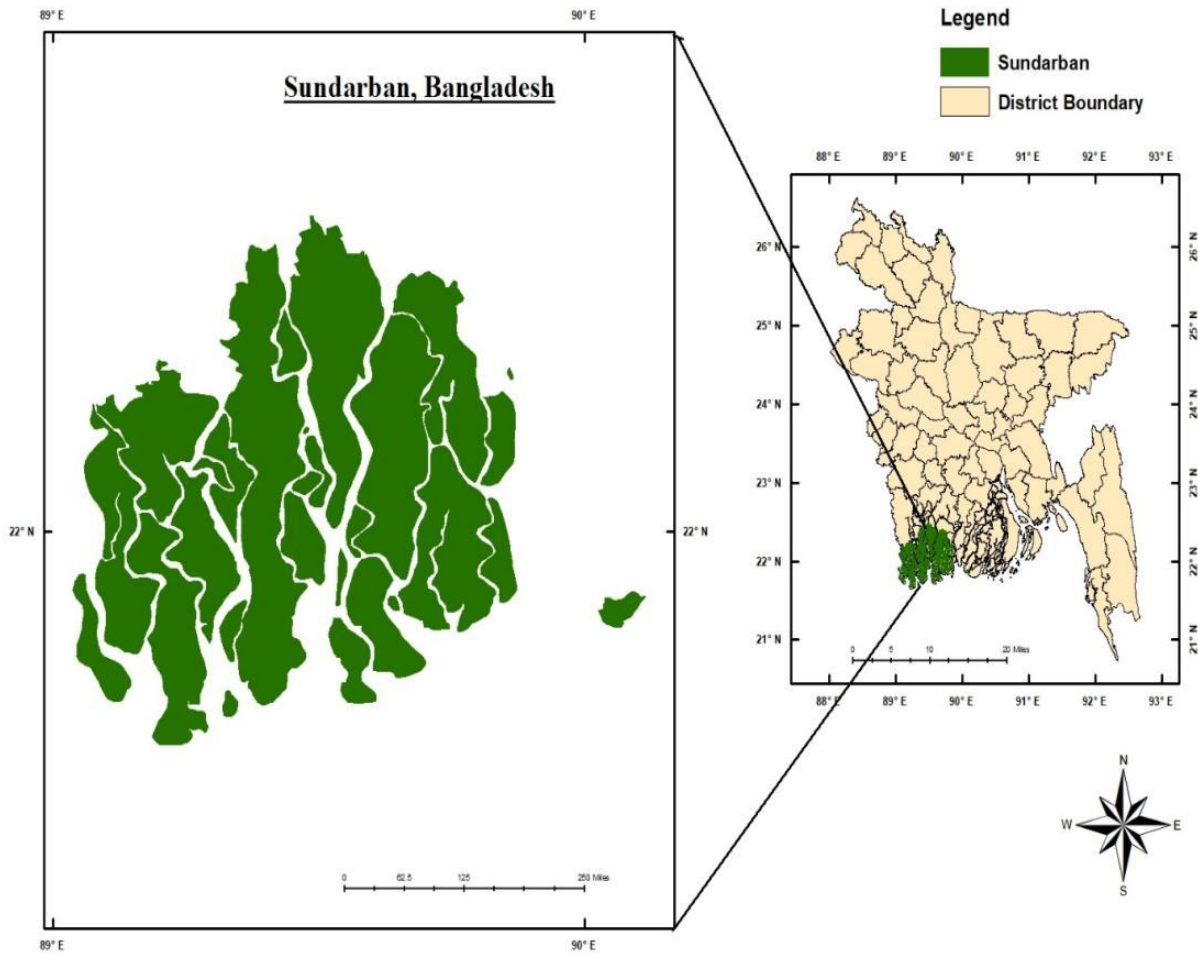


Figure 1. Geographic setting of the Sundarbans mangrove ecosystem in southwestern Bangladesh.

Satellite Image Acquisition and Pre-processing

Cloud-free Landsat 5 TM and Landsat 8 OLI surface reflectance imagery (30 m spatial resolution) was retrieved from the United States Geological Survey (USGS) EarthExplorer database. Image pairs were selected to capture conditions immediately prior to and following cyclones Aila (2009) and Bulbul (2019).

- Aila Imagery: February 19/28, 2009 (Pre-Aila) and November 02/11, 2009 (Post-Aila) (Path/Row 137/45 and 138/45)
- Bulbul Imagery: February 15/24, 2019 (Pre-Bulbul) and January 26/February 02, 2020 (Post-Bulbul) (Post-Bulbul) (Path/Row 137/45 and 138/45)

Pre-processing steps included cloud/shadow masking, atmospheric correction using LaSRC/LEADPS algorithms, band alignment, spatial mosaicking, and clipping to the official forest administrative boundary in ArcGIS 10.8.

Spectral Vegetation Indices

Two vegetation indices were calculated from surface reflectance values for evaluating the spatial and temporal changes in vegetation cover:

Normalized Difference Vegetation Index (NDVI)

NDVI is a widely used spectral index for measuring live green vegetation based on the difference in high reflectance between the near-infrared (NIR) spectrum and high absorption in the red band. It is calculated using the following formula:

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

Where:

- NIR = Near-infrared band (Band 4 for Landsat 5 TM, Band 5 for Landsat 8 OLI)
- Red = Red band (Band 3 for Landsat 5 TM, Band 4 for Landsat 8 OLI)

NDVI values range from -1 to +1, where values near +1 indicate dense vegetation, values close to 0 indicate sparse or stressed vegetation, and negative values typically represent water bodies or non-vegetated surfaces.

Enhanced Vegetation Index (EVI)

EVI is designed to optimize the vegetation signal in dense biomass region by incorporating corrections for canopy background and atmospheric conditions. The mathematical expression of EVI is as follows:

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

Where:

- G = 2.5 (gain factor)
- C₁ = 6.0 (aerosol resistance coefficient for the red band)
- C₂ = 7.5 (aerosol resistance coefficient for the blue band)
- L = 1.0 (canopy background adjustment factor)
- Blue = Blue band (Band 1 for Landsat 5 TM and Band 2 for Landsat 8 OLI)

EVI values usually range from 0 to 1, with higher values indicating more vigorous vegetation.

Image Classification and Thresholding

Unsupervised Classification

A classification scheme that was not subject to supervision was implemented, utilizing the Iterative Self-Organizing Data Analysis Technique (ISODATA) clustering algorithm for the purpose of identifying major land cover types and cyclone-affected zones. The continuous spatial clusters were categorized into six land use/land cover (LULC) classes: Water, Built-up Area, Barren Land, Shrubs and Grassland, Sparse Vegetation, and Dense Vegetation.

NDVI-Based Reclassification

Following the threshold proposed by Akbar et al. (2019), continuous index outputs were segmented into six discrete categories to systematically classify mangrove vegetation density and vegetation health (Table 1).

Table 1: Reclassification thresholds and corresponding land cover classes (Akbar et al., 2019)

NDVI/Index Range	Land Cover/Vegetation Class
-0.280 to 0.015	Water Bodies
0.015 to 0.140	Built-up Area
0.140 to 0.180	Barren Land
0.180 to 0.270	Shrubs and Grassland
0.270 to 0.360	Sparse Vegetation
0.360 to 0.740	Dense Vegetation

Area Estimation

The surface area occupied by each classified land cover type was calculated by extracting pixel-level raster statistics. Given the spatial resolution of 30 m × 30 m (900m² pixel size), for both Landsat 5 TM and Landsat 8 OLI imagery, the total area (A) in square kilometers was computed as:

$$A = \frac{N \times (30 \times 30)}{1000000} = N \times 0.0009$$

Where,

- A = Total area in square kilometers (km²)
- N = Number of pixels in a particular land cover class
- 30 × 30 = Pixel dimensions in meters (900 m²)
- 1000000 = Conversion factor from m² to km²

Post-Classification Change Verification and Statistical Significance Testing

This study determined whether the calculated post-cyclone land cover transformations were statistically significant or just random classification noise. The McNemar's Chi-Square (χ^2) was applied to paired cross-tabulated pixel transition metrics:

$$\chi^2 = \frac{(\sum 12 - \sum 21)^2}{(\sum 12 + \sum 21)}$$

Where:

$\sum 12$ = Number of pixels changing from class 1 to class 2.

$\sum 21$ = Number of pixels changing from class 2 to class 1.

A significance level of $p < 0.05$ was used. Additionally, paired t-tests were applied to continuous vegetation index values (NDVI, EVI) to evaluate average vegetation changes across cyclone periods.

Results

Vegetation Status Before and After Cyclone Aila (2009)

Cyclone Aila made landfall on May 25, 2009, significantly affecting the central and southwestern parts of the Sundarbans. McNemar test χ^2 confirmed that pre- and post-cyclone spatial assessments for Cyclone Aila were statistically significant ($\chi^2 = 1482.64$; $p < 0.001$). Paired t-tests further verified significant mean shifts in both NDVI ($t=14.82$, $p < 0.001$) and EVI ($t=19.45$, $p < 0.001$) values.

NDVI-Based Classification

Before Aila (February 2009), dense vegetation dominated the landscape, covering 2803.90 km² (64.46%). Following the cyclone (November 2009), sparse vegetation exhibited a severe contraction, declining by 679.81 km² (-88.12%). Shrubs and grassland similarly contracted from 109.75 km² to 52.16 km² (-52.47%). Conversely, dense vegetation exhibited a net increase of 772.31 km² (+27.54%). Water bodies expanded by 6.49 km², indicating localized bank erosion and storm surge flooding (Table 2; Figure 2).

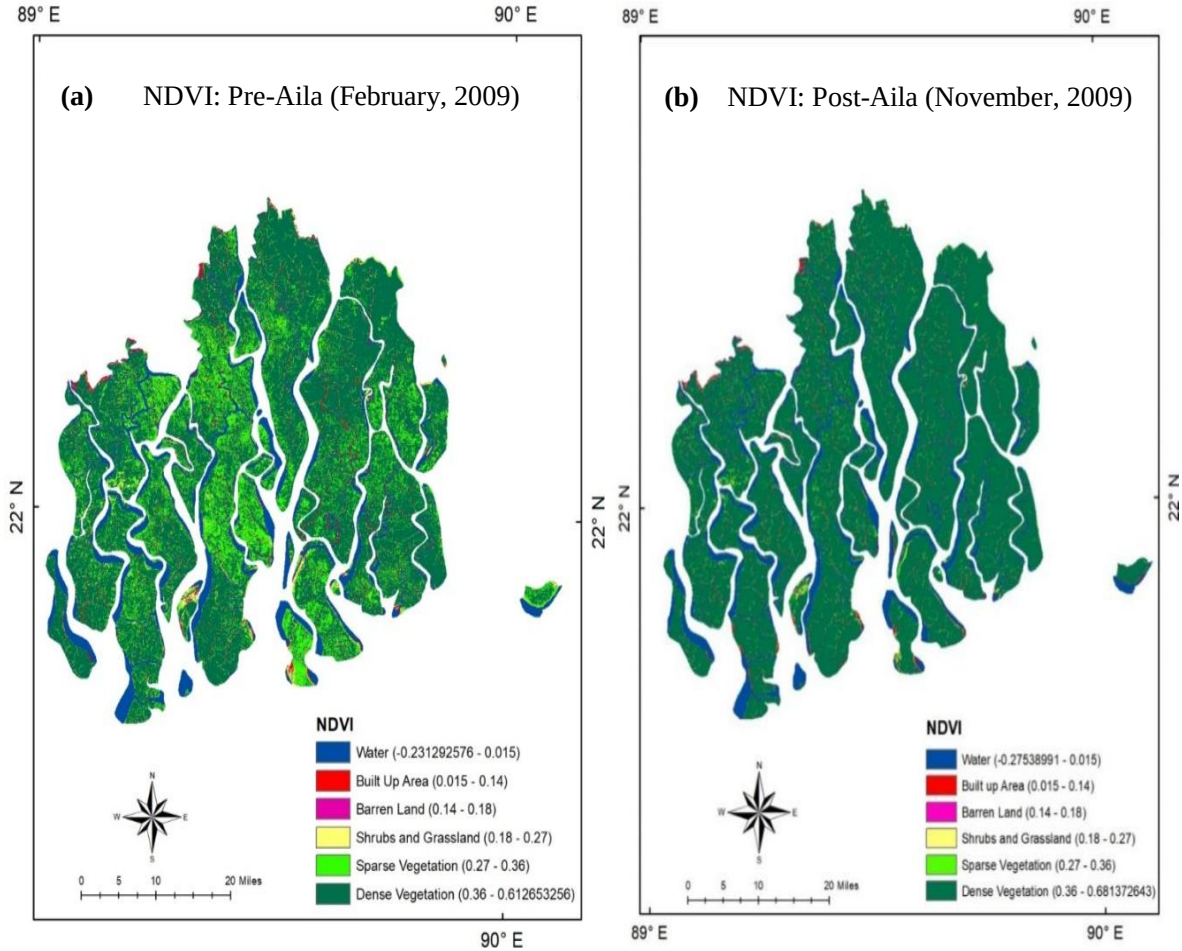


Figure 2. Spatial distribution of NDVI-derived land cover classes in the Bangladeshi Sundarbans before and after Cyclone Aila: (a) Pre-cyclone baseline (February 2009), and (b) Post-cyclone state (November 2009)

Table 2. Standard Three-Line Table showing quantitative assessment of vegetation dynamics before and after Cyclone Aila (February 2009 vs. November 2009)

Land Cover Class	Pre-Aila (km ²)	Pre-Aila (%)	Post-Aila (km ²)	Post-Aila (%)	Net Change Δ (km ²)	Relative Change (%)
Water Bodies	524.76	12.06	531.25	12.21	+6.49	+1.24
Built up Area	107.79	2.48	78.59	1.81	-29.20	-27.09
Barren Land	32.22	0.74	20.03	0.46	-12.19	-37.83
Shrubs and Grassland	109.75	2.52	52.16	1.20	-57.59	-52.47
Sparse Vegetation	771.45	17.74	91.64	2.11	-679.81	-88.12
Dense Vegetation	2803.90	64.46	3576.21	82.21	+772.31	+27.54
Total	4349.88	100	4349.88	100	0.00	---

EVI-Based Classification

EVI analysis optimized the vegetation signal in dense biomass regions by correcting for atmospheric conditions and soil background reflectance. Before cyclone Aila (in February 2009), shrubs and grassland covered most of the EVI-derived map, with 2,877.62 km² (66.15%) of the area. Sparse vegetation occupied 635.56 km² (14.61%), and dense vegetation covered only 9.06 km² (0.21%). After the cyclone (in November 2009), shrubs and grassland shrank dramatically, losing 2563.37 km² (-89.08%) of their extent. In contrast, sparse vegetation grew from 635.56 km² to 2542.06 km², resulting in a net increase of 1906.50 km² (+299.97%). Dense vegetation also grew, rising from 9.06 km² to 787.22 km², an increase of 778.16 km² (+8588.96%). Water bodies increased a little up 1.27 km² (+0.23%), indicating storm surge inundation areas and localized shoreline erosion (Table 3, Figure 3). These structural changes show how severely the storm damaged and submerged low-lying understory plants. In contrast, the deeper-rooted, mature mangrove trees maintained their root stability and rapidly regained new leaves after the monsoon.

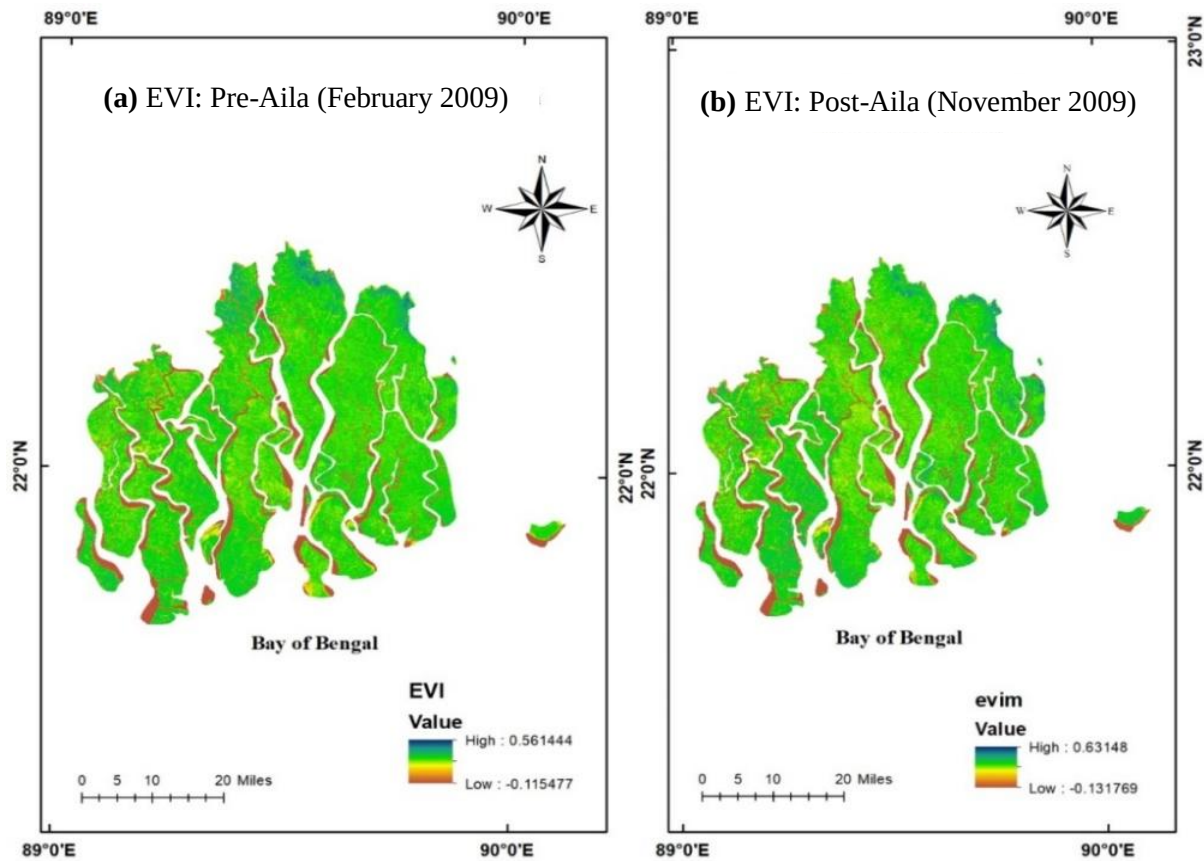


Figure 3. Spatial distribution of EVI-derived land cover classes in the Bangladeshi Sundarbans before and after Cyclone Aila: (a) Pre-cyclone baseline (February 2009), and (b) Post-cyclone state (November 2009).

Table 3. Quantitative assessment of vegetation dynamics before and after Cyclone Aila based on EVI classification (February 2009 vs. November 2009)

Land Cover Class	Pre-Aila (km ²)	Pre-Aila (%)	Post-Aila (km ²)	Post-Aila (%)	Net Change Δ (km ²)	Relative Change (%)
Water Bodies	541.08	12.44	542.35	12.47	+1.27	+0.23
Built up Area	176.01	4.05	120.6	2.77	-55.41	-31.48
Barren Land	110.56	2.54	43.4	1.00	-67.16	-60.74
Shrubs and Grassland	2877.62	66.15	314.25	7.22	-2563.37	-89.08
Sparse Vegetation	635.56	14.61	2542.06	58.44	+1906.50	+299.97
Dense Vegetation	9.06	0.21	787.22	18.10	+778.16	+8588.96
Total	4349.88	100	4349.88	100	0.00	---

Change Detection Summary and Ecological Justification (Cyclone Aila)

Change detection using NDVI and EVI (Figures 2 and 3; Tables 2 and 3) demonstrated that sparse vegetation fell sharply while dense vegetation rose. This means there was a spatio-temporal shift in vegetation spectral classes, not a quick jump in total forest biomass. I find this interesting because it matches what Mondal et al. (2022) Reported, showing that shorter mangrove trees were hit harder, than more mature trees.

The growth of vegetation which increased by 772.31 km² in NDVI and the significant decline in sparse vegetation decreasing by 88.12 km² can be explained by seasonal changes in plant behavior and how the sensor captures data. The pre-cyclone baseline images taken in February 2009 were captured during the dry season. During this time rainfall was low and soil salinity was high leading to a lower leaf area index or LAI. These conditions limited plant growth, especially, for sparse vegetation while denser vegetation showed more resilience and expanded its coverage. Cyclone Aila hit in May 2009, after which the intensive monsoon season began (June–October). The substantial influx of freshwater from upstream river systems washed away soil salts, stimulating aggressive leaf flushing (epicormic sprouting) in surviving climax species, such as *Heritiera fomes* and *Excoecaria agallocha*.

By November 2009 (post-monsoon acquisition), the remaining plants had strong near-infrared reflectance, resulting in widespread reclassification of pixels from sparse to dense canopy cover. Meanwhile, fragile understorey vegetation and low-lying shrubs were washed away or smothered by storm surge sediments, resulting in a significant contraction of the shrubland and sparse categories.

Vegetation Status Before and After Cyclone Bulbul (2019/2020)

McNemar's chi-squared test confirmed the statistical significance of land cover changes after Cyclone Bulbul ($\chi^2 = 845.12$, $p < 0.001$). Paired t-test evaluations confirmed significant multi-temporal spectral index shifts ($p < 0.001$), showing that the observed changes were genuine spatial reorganisations rather than random classification errors.

NDVI-Based Classification (Cyclone Bulbul)

Cyclone Bulbul hit in November 2019 and had a major impact on the southwestern Sundarbans. To understand the changes, satellite images from February 2019 and February 2020 were used. These two points, in time represented the condition before the cyclone and the condition one year after. In February 2019 before the cyclone the area was mostly covered in vegetation and spanned 3314.73 km², which was 76.20% of the area. After the cyclone in February 2020 the vegetation had shrunk. The dense plant cover

decreased dramatically by 138.49 km², which was a drop of 45.65%. This showed a loss of green cover in the region after Cyclone Bulbul passed through. Shrubs and grassland similarly contracted from 72.63 km² to 57.97 km² (-20.18%). Conversely, dense vegetation exhibited a net increase of 154.69 km² (+4.67%). Water bodies expanded by 24.30 km² (+4.67%), indicating localized bank erosion and storm surge flooding (Table 4; Figure 4).

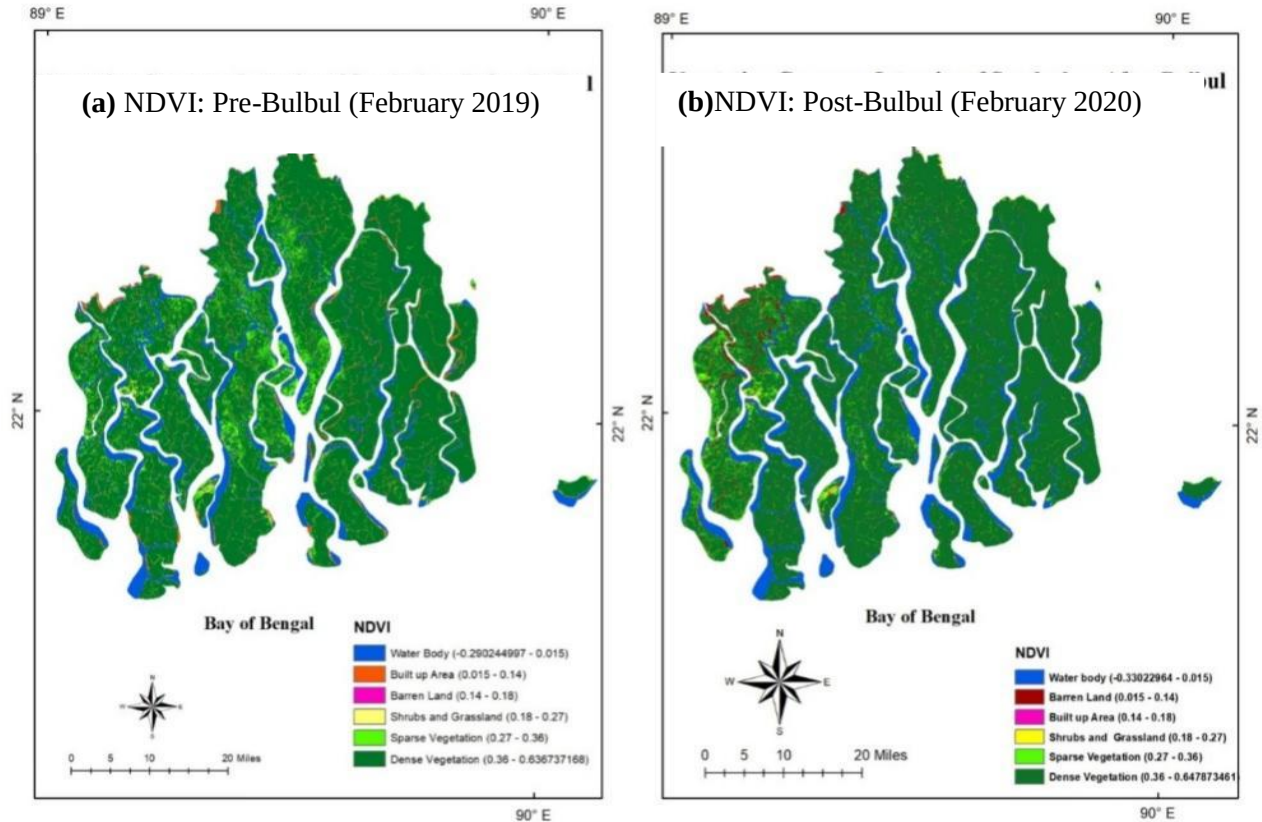


Figure 4. Spatial distribution of NDVI-derived land cover classes in the Bangladeshi Sundarbans before and after Cyclone Bulbul: (a) Pre-cyclone baseline (February 2019), and (b) Post-cyclone state (February 2020).

Table 4. Quantitative assessment of vegetation dynamics before and after Cyclone Bulbul based on NDVI classification (February 2019 vs. February 2020).

Land Cover Class	Pre-Bulbul (km ²)	Pre-Bulbul (%)	Post-Bulbul (km ²)	Post-Bulbul (%)	Net Change Δ (km ²)	Relative Change (%)
Water Bodies	520.88	11.97	545.18	12.53	+24.30	+4.67
Built up Area	114.13	2.62	91.28	2.10	-22.85	-20.02
Barren Land	24.13	0.55	21.14	0.49	-2.99	-12.39
Shrubs and Grassland	72.63	1.67	57.97	1.33	-14.66	-20.18
Sparse Vegetation	303.39	6.97	164.90	3.79	-138.49	-45.65
Dense Vegetation	3314.73	76.20	3469.42	79.76	+154.69	+4.67
Total	4349.88	100	4349.88	100	0.00	----

EVI-Based Classification (Cyclone Bulbul)

Prior to Bulbul (February 2019), shrubs and grassland dominated the EVI-derived landscape, covering 2138.41 km² (49.16%), while sparse vegetation occupied 1385.23 km² (31.85%) and dense vegetation accounted for 19.47 km² (0.45%). Following the cyclone (February 2020), shrubs and grassland exhibited a severe contraction, declining by 1334.21 km² (-62.39%). In contrast, our EVI data show a sharp expansion in sparse vegetation, which rose from 1385.23 km² to 2612.96 km², recording a net increase of 1227.73 km² (+88.63%). We observed a similar upward trend in dense vegetation, climbing from 19.47 km² up to 184.70 km², adding a total of 165.23 km² (+848.64%) to its coverage. Water bodies remained relatively stable, decreasing slightly by just 1.00 km² (-0.18%) (Table 5; Figure 5). This response highlights a clear divide in forest resilience: high-velocity winds and surges easily drowned the fragile understory vegetation layer, but the deeper-rooted, mature mangrove trees maintained root system integrity and underwent rapid canopy foliage recovery.

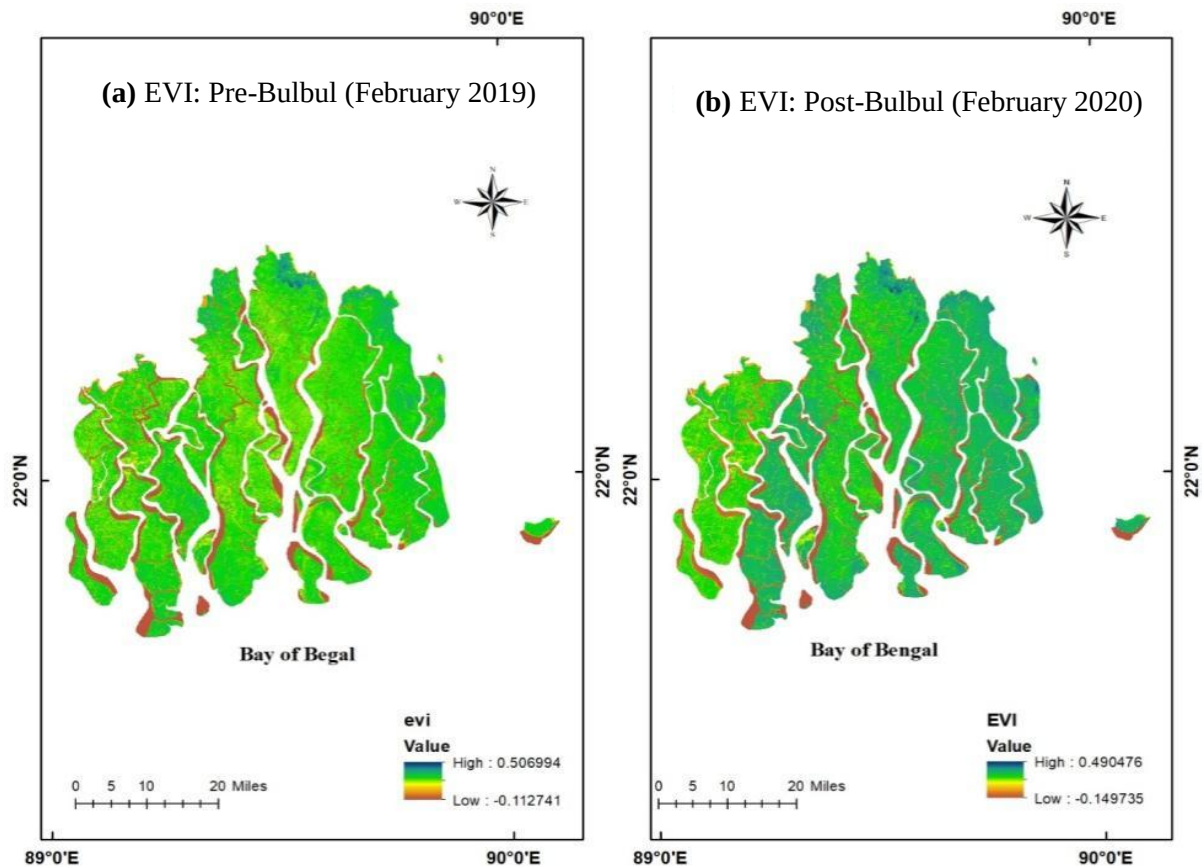


Figure 5. Spatial distribution of EVI-derived land cover classes in the Bangladeshi Sundarbans before and after Cyclone Bulbul: (a) Pre-cyclone baseline (February 2019), and (b) Post-cyclone state (February 2020).

Change Detection Synthesis and Ecological Justification (Cyclone Bulbul)

The multi-temporal analysis in this study used NDVI and EVI to look at how the southwestern Sundarbans canopy responded to Cyclone Bulbul (see Figures 4 and 5). When looking at the NDVI maps there was a drop in vegetation, by 138.49 km², which is a decline of 45.65 percent. At the time dense forest cover increased by 154.69 km², a rise of 4.67 percent. Using EVI data showed stronger signs of change. Shrublands and ground vegetation decreased by an amount—1354.28 km² or 62.74 percent. In contrast

sparse vegetation went up by 1227.73 km², an increase of 88.63 percent and dense forest layers grew by 165.23 km², which's a huge jump of 848.64 percent (see Tables 4 and 5).

A key advantage of this study is that the images for Cyclone Bulbul come from the month in back-to-back years (February 2019 baseline versus February 2020 post-cyclone). This was not possible for Cyclone Aila. By avoiding changes that happen with the seasons it was possible to make sure that these changes in the trees show recovery of plant species and not just effects, from the weather.

Table 5. Quantitative assessment of vegetation dynamics before and after Cyclone Bulbul based on EVI classification (February 2019 vs. February 2020).

Land Cover Class	Pre-Bulbul (km ²)	Pre-Bulbul (%)	Post-Bulbul (km ²)	Post-Bulbul (%)	Net Change Δ (km ²)	Relative Change (%)
Water Bodies	561.67	12.91	560.67	12.89	-1.00	-0.18
Built up Area	165.56	3.81	134.90	3.10	-30.66	-18.52
Barren Land	79.54	1.83	52.44	1.21	-27.10	-34.07
Shrubs and Grassland	2138.41	49.16	804.20	18.49	-1334.21	-62.39
Sparse Vegetation	1385.23	31.85	2612.96	60.07	+1227.73	+88.63
Dense Vegetation	19.47	0.45	184.70	4.25	+165.23	+848.64
Total	4349.88	100.00	4349.88	100.00	0.00	----

The sharp loss of plants that grow close to the ground was because of physical damage and saltwater flooding when the storm came through. Unlike this older trees that have roots and are at the top of the forest like *Heritiera fomes* (Sundari) and *Excoecaria agallocha* (Gewa) were able to stay strong with their roots even when the sea water came in. From November 2019 to February 2020 these trees grew a lot of shoots and new leaves. This quick growth of leaves on the part of the trees made the near-infrared (NIR) signal stronger, in areas that had been hurt before. This made the pictures of those areas show as green plants again showing how strong the top part of the forest can be.

Statistical Significance Verification of Land Cover Transitions and Spectral Index Shifts

We conducted statistical significance tests for both cyclonic events to confirm that the observed spatial shifts and index changes reflect genuine ecological variation rather than random classification noise or sensor errors (see Table 6). McNemar's tests on the cross-tabulated pixel matrices showed highly significant results for both Cyclone Aila ($\chi^2 = 1,482.64$, $p < 0.001$) and Cyclone Bulbul ($\chi^2 = 845.12$, $p < 0.001$) for the categorical land-cover changes. Additionally, paired two-sample t-tests evaluating variations in continuous NDVI and EVI pixel values before and after each storm showed highly significant mean shifts ($p < 0.001$). These statistical indicators prove that the documented patterns of canopy damage and post-disaster recovery are statistically robust.

Table 6. Statistical significance verification of pre- and post-cyclone vegetation indices and land-cover transitions.

Cyclonic Event	Index/ Transition Type	Test Performed	Test Value	Statistic	Degree of Freedom (df)	P Value	Statistical Inference
Cyclone Aila (2009)	Pixel Transition Matrix	McNemar's (χ^2)	$\chi^2 = 1482.64$		1	$p < 0.001$	Statistically Significant
	Mean NDVI Shift	Paired t-test	$t = 14.82$		N-1	$p < 0.001$	Statistically Significant
	Mean EVI Shift	Paired t-test	$t = 19.45$		N-1	$p < 0.001$	Statistically Significant
Cyclone Bulbul (2019)	Pixel Transition Matrix	McNemar's (χ^2)	$\chi^2 = 845.12$		1	$p < 0.001$	Statistically Significant
	Mean NDVI Shift	Paired t-test	$t = 11.34$		N-1	$p < 0.001$	Statistically Significant
	Mean EVI Shift	Paired t-test	$t = 16.78$		N-1	$p < 0.001$	Statistically Significant

Interpretation and Comparative Synthesis (Aila vs. Bulbul)

A comparison of the vegetation responses to Cyclone Aila (2009) and Cyclone Bulbul (2019) reveals consistent ecological trends. However, it is important to note the significant differences caused by the timing of the satellite image acquisitions. This is supported by the strong confirmation from McNemar's χ^2 tests ($p < 0.001$) and paired t-tests ($p < 0.001$) that the spatial redistributions and spectral index shifts for both storms were statistically significant and non-random.

In the context of both cyclonic events, the short-stature understory, comprising shrubs and grassland class, emerged as the most vulnerable components of the forest. Analysis of EVI data reveals a pronounced decline in this category, with shrubs experiencing a 89.08% loss (-2,563.37 km²) following Aila and a 62.74% loss (-1,354.28 km²) after Bulbul. This substantial loss underscores the vulnerability of fragile pioneer species and understory plants to intense wind stripping, uprooting, and prolonged saltwater flooding.

In contrast, the older and denser groups showed physical strength. These mature tree groups had growth after both events as shown by NDVI results (+27.54% for Aila; +4.67% for Bulbul) and EVI results (+8588.96% for Aila; +848.64% for Bulbul). This unexpected change from a canopy, to a thick canopy area can be explained by two main reasons:

- **Phenological Greening versus True Recovery:** The post-Aila tracking window from February to November 2009 spanned the monsoon season from June to October. This season brought heavy freshwater flows. The strong runoff removed built-up soil salts. Helped surviving canopy trees, such as *Heritiera fomes* (Sundari) and *Excoecaria agallocha* (Gewa) grow new shoots and leaves. The burst of growth raised near-infrared reflectance. Made satellite images show a temporary greening that marked pixels as dense vegetation. In contrast the post-Bulbul tracking used images taken in the month in consecutive years, February 2019 and February 2020. This comparison isolated physiological recovery and new sprouting that happened in a short three-month period, after the storm.
- **Species-Specific Canopy Stratification:** Deep-rooted, mature trees stayed strong during strong wind and big waves. They kept the forest tall and organized. Even though the storm waves took away the

leaves and broke the soft plants on the ground the top layer of the forest grew new leaves quickly. This accelerated leaf growth obscured the damaged understory layers beneath it and dominated the satellite sensor's overall pixel signal.

Furthermore, the expansion of water channels during both storms (+1.27 km² after Aila and +24.30 km² after Bulbul in our NDVI maps) points to ongoing shoreline erosion, riverbank failure, and long-lasting flooding after the initial storm surges have passed.

When considered collectively, these trends – which are strongly supported by significant statistical check matrices ($p < 0.001$) – reveal the complex nature of the Sundarbans. The ecosystem combines a highly fragile understory layer with a resilient upper canopy capable of rapid healing. However, even if mature stands show quick initial leaf growth, being hit by severe storms more frequently could deplete the carbohydrate stores needed for new shoots. Over time, this could shift the balance of local tree species and cause long-term canopy degradation if the situation is not tracked carefully using multi-index satellite frameworks.

Conclusion and Recommendations

Conclusion

The Sundarbans, a case study of a mangrove forest have been identified as the world's continuous one. Its importance lies in its function in protecting coastlines supporting biodiversity and carbon sequestration. However the ecosystem is under threat, from frequent and severe tropical cyclones, exacerbated by global climate change. This study examined the spatio-vegetation dynamics and canopy structural transformations of the Sundarbans before and after Cyclone Aila (2009) and Cyclone Bulbul (2019) using multi-index satellite observations derived from NDVI and EVI.

The findings indicate that both cyclones caused damage to vegetation. The damage was especially strong in sparse vegetation, shrub land and the lower parts of the canopy. The damage happened because wind ripped the plants away and storm surge flooded the area. After Cyclone Aila sparse vegetation fell by 679.81 km², which's an 88.12 percent drop while dense vegetation grew by 772.31 km², a 27.54 percent increase. After Cyclone Bulbul sparse vegetation fell by 138.49 km², a 45.65 percent drop and dense vegetation grew by 154.69 km², a 4.67 percent rise. A multi-spectral EVI analysis confirmed that mature, deep-rooted canopy stands recovered more than sparse vegetation showing that species have different structural strengths against storm forces. Additional statistical tests, like McNemar's chi-square and paired t-tests with $p < .001$ proved that the changes, in land cover and steady spectral shifts were ecological reorganisations and not random.

The study shows that short-term vegetative greening after a cyclone is greatly influenced by post-monsoon flushing, which is a type of epicormic regrowth that happens when freshwater salinity falls together with the real physiological recovery of the trees. The Sundarbans has demonstrated an ability for natural regeneration yet this vegetative greening process is not uniform and is not guaranteed under the increasing pressures of climate change. Repeated cyclonic events within return periods ultimately weaken long-term storage and the structural stability of mangroves. Thus multi-index remote sensing frameworks that incorporate phenology are essential for accurately monitoring mangrove health and, for guiding ecosystem-based management and coastal resilience strategies.

Recommendations

This study highlights the importance of using vegetation indices like NDVI and EVI to track how mangroves come back after cyclones. The work should focus on places where there has been a loss of thin vegetation. Growing mangrove species that are used to the area in these places can help them grow back on their own. Adding sensing to regular checks can help spot changes in plants sooner. Even though this study didn't look at this directly making sure the work fits with plans like the Delta Plan 2100 and involving local people can help mangroves stay strong for a long time.

From what has been seen about how mangrove plants are lost and then grow back the following steps, for policy and management are suggested:

- **Targeted Spatial Restoration** In the context of ecological restoration and post-disaster interventions, there is a compelling argument for focusing on highly vulnerable zones that have suffered severe understory shrinkage. This is particularly the case in areas where pioneer shrubs and sparse vegetation are present along cyclone tracks.
- **In the context of species-specific reforestation**, it is imperative that restoration plans prioritise the utilisation of deep-rooted, storm-resilient climax species. Such species, which include *Heritiera fomes* and *Excoecaria agallocha*, possess a high degree of structural resistance and rapid epicormic regrowth capabilities. These characteristics are crucial in ensuring the stability of fragile intertidal banks, which can be particularly vulnerable to the effects of climate change. In addition to these climax species, the inclusion of locally adapted pioneer species is recommended, as they have the capacity to colonise and stabilise new environments.
- **The Importance of Phenology-Aware Remote Sensing Frameworks for National Forest and Environmental Agencies** It is imperative that national forest and environmental agencies incorporate continuous multi-spectral satellite monitoring into their daily management practices. Remote sensing frameworks must take into account post-monsoon phenology to accurately differentiate between short-term physiological greening and long-term biomass recovery.
- **The Integration of Policy and Community Stewardship in Post-Cyclone Management** It is imperative that management plans following a cyclone align with long-term coastal planning initiatives, such as the Delta Plan 2100 implemented in Bangladesh. These plans must involve local coastal communities in the active management process, with a focus on the protection of fringe mangroves and the guidance of young saplings to prevent displacement caused by tidal surges.

Authorship Contribution

Md. Touhiduzzaman was responsible for the conceptualisation, methodology, statistical analysis, visualisation, data curation, writing – review and editing, and validation. **Afrin Akter Akhi** was responsible for the conceptualisation, methodology, investigation, resources, data curation, and writing – original draft. **Md. Saifur Rahman** was responsible for the conceptualisation, supervision, project administration, validation, and writing – review and editing. **Mawya Siddeqa** was responsible for the investigation, resources, and writing – review and editing.

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