



Understanding The Consideration Of Cyclone Bulbul In Assessing Ecological Changes In South-West Village Fringe Mangroves Of The Indian Sundarbans

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Abstract: The village-fringe mangroves of the Sundarbans serve as crucial bio-shields against storms, surges, and erosion. However, long-term unsustainable resource use and hydro-geomorphic changes have degraded these ecosystems. Cyclone Bulbul (9th November 2019), with 119 km/h winds, caused widespread damage. This study analyses its impact on vegetation and canopy gaps across five village-fringe sites in the south-western Sundarbans using Landsat-8 data. Dense canopies were severely degraded, especially in North-Bakkhali and Shikarpur, while Dwarikanagar saw lesser impact but signs of vegetation decline. The findings highlight the urgent need for periodic, site-specific monitoring and sustainable management to restore and protect the ecological health of these vulnerable mangrove zones.

Index Terms: Sundarbans, Cyclone Bulbul, mangroves, canopy gap formation, vegetation dynamics, coastal erosion, sustainable management, ecosystem restoration.

I. INTRODUCTION

Mangroves are vital coastal ecosystems distributed globally across tropical and subtropical coastlines, covering approximately 15.2 million hectares. They represent 0.7% of tropical forests and play an indispensable role in shoreline stabilization, storm protection, carbon sequestration, and supporting biodiversity (Giri et al., 2010; Bal and Banerjee, 2020). South Asia accounts for about 7% of global mangrove cover, with India contributing approximately 4,921 sq. km, or 3% of the region's total. Among these, the Sundarbans, shared between India and Bangladesh, is the largest contiguous mangrove forest globally. Recognized as a World Heritage Site by the IUCN in 1987 and a Biosphere Reserve by UNESCO in 1989, the Sundarbans support diverse ecological and physical processes. These mangroves regulate sediment accretion, stabilize younger alluviums, act as bio-shields, and facilitate nutrient recycling and carbon exchange between terrestrial and marine ecosystems (Paul et al., 2017).

Fringe mangroves in the Sundarbans, located on the coastal edges of deltaic islands, serve as critical buffers against tidal surges and cyclonic disturbances. However, these ecosystems are under increasing threat due to socio-economic pressures and human interventions. Overpopulation, poverty, and dependency on mangrove resources have led to unsustainable practices such as timber extraction, fuelwood collection, and agricultural encroachment (Datta, 2018). Additionally, aquaculture expansion and infrastructure development have degraded mangrove health, making the vegetation more vulnerable to natural disasters (Datta and Deb, 2012; Paul et al., 2017).

Cyclone Bulbul, which struck the Sundarbans on November 9, 2019, exemplifies the fragile balance between ecological resilience and socio-economic stressors. With wind speeds surpassing 120 km/h, the cyclone caused widespread damage to mangrove vegetation and local livelihoods. Vast tracts of fringe mangroves were uprooted or defoliated, leading to increased soil erosion, saltwater intrusion, and habitat disruption (Thakur et al., 2020). For marginal farmers and fishermen reliant on these ecosystems, the immediate impacts included loss of shelter, diminished agricultural productivity, and long-term economic challenges, such as reduced income from aquaculture and food insecurity (Chowdhury et al., 2019; Datta, 2018).

This study leverages the immediate aftermath of Cyclone Bulbul to investigate the changes in mangrove health and coverage caused by such extreme climatic events. Using satellite-derived NDVI and fragmentation analysis, the research evaluates the spatial and temporal impacts of the cyclone on fringe mangrove ecosystems in the Indian Sundarbans. By incorporating socio-economic data, the study also explores the compounded effects of human activities and natural disasters on mangrove degradation and resilience.

Through this integrated approach, the research highlights the dual vulnerabilities faced by mangrove ecosystems and dependent coastal communities. It underscores the critical role of sustainable management practices in ensuring the resilience of mangroves, which act as ecological keystones and socio-economic lifelines. The findings aim to inform conservation strategies and adaptive measures to mitigate the escalating impacts of climate-related threats on the Sundarbans' mangrove ecosystems and the livelihoods they support (Paul et al., 2017; Datta and Deb, 2012).

II. MATERIALS AND METHODS

2.1 Study Site Selection

The study focuses on the shoreline mangrove forests of Namkhana and Kakdwip C.D. Blocks in the Indian Sundarbans. Five major village-fringe mangrove sites within these blocks were selected based on their proximity to the cyclone path and distance from the Bay of Bengal, representing areas with vegetation thinning and density variations due to cyclonic impacts (Datta and Deb, 2012; Paul et al., 2017).

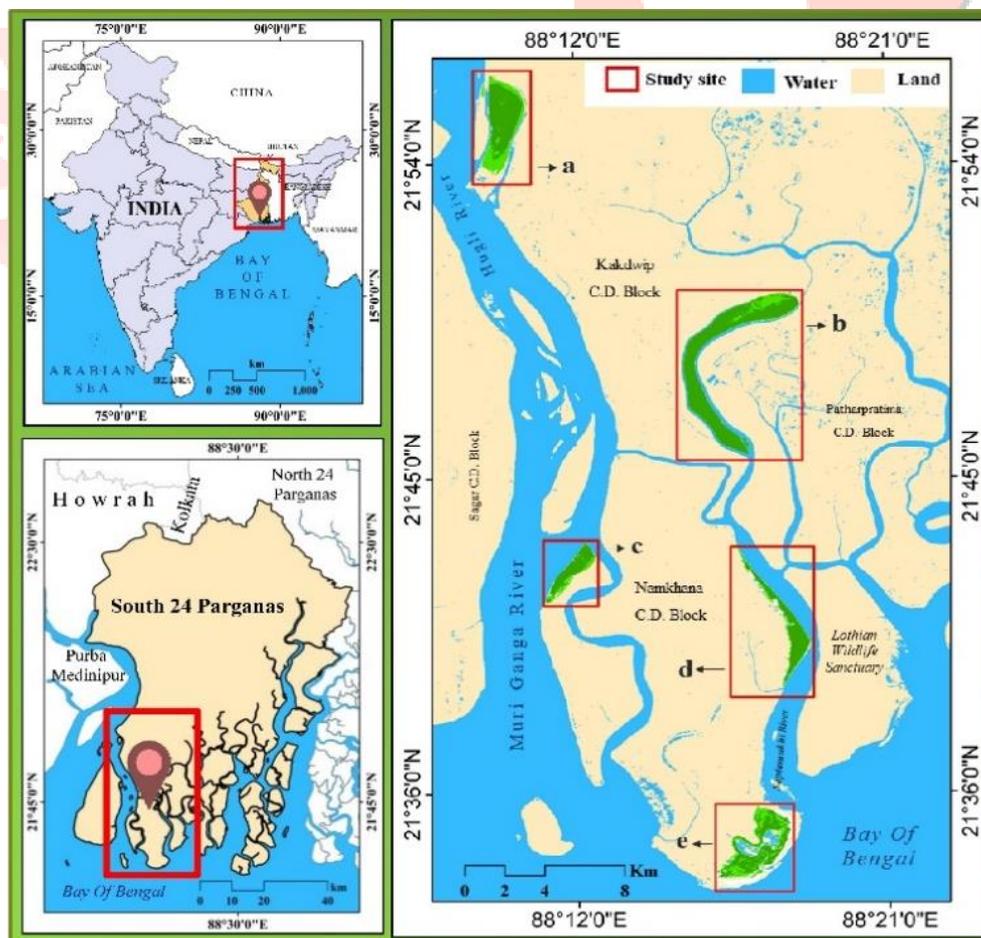


Figure 1: Location map of the study sites a. Sibkalinagar b. Dwarikanagar c. North-Mousuni d. Shikarpur e. North-Bakkhali

Namkhana C.D. Block spans 227.45 sq. km, located between 21°49' N, 88°11' E and 21°33' N, 88°20' E. It is bordered by Patharpratima C.D. Block and the Saptamukhi River to the east, Kakdwip C.D. Block to the north, the Bay of Bengal to the south, and Sagar C.D. Block to the west. Kakdwip C.D. Block, covering 252.74 sq. km, lies between 22°0' N, 88°9' E and 21°48' N, 88°21' E. It is bordered by Kulpi C.D. Block to the north, Patharpratima C.D. Block to the east, Namkhana and Sagar C.D. Blocks to the south, and Nandigram (I) C.D. Block to the west. Both blocks are situated in the southwestern part of the Sundarbans, with an average elevation of 4 meters (Figure 1). The population of these blocks is about 500,000 people, the vast majority of whom are small-scale farmers and fishermen. The area experiences an average annual rainfall of 1750 to 1770 mm, with temperatures reaching up to 38°C in summer and dropping to 13.5°C in winter. These characteristics make the region a critical site for assessing cyclone impacts on mangrove ecosystems (Census of India, 2011; Dhara and Paul, 2016; Department of Sundarban Affairs, 2018).

2.2 Methodology

This study employs a multi-step methodology involving database development, preprocessing of satellite data, study site selection, bio-physical indicator-based mapping, vegetation change analysis, and canopy gap dynamics assessment to evaluate the immediate impacts of Cyclone Bulbul on fringe mangrove forests, along with an analysis of the cyclone's path across the study region (Figure 2).

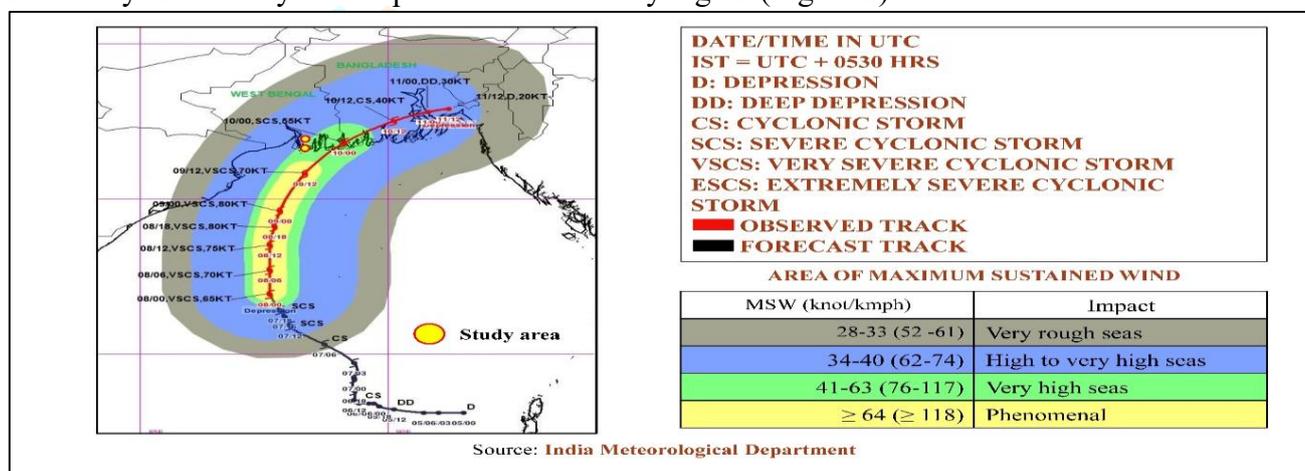


Figure 2: Trajectory of Cyclone Bulbul across the study area

2.3 Data Acquisition and Pre-processing

Cloud-free Landsat 8 OLI-TIRS imagery (Path-Row: 138-045) was obtained from the USGS EarthExplorer platform. The pre-cyclone image was acquired on October 29, 2019 (11 days before landfall), and the post-cyclone image was collected on November 30, 2019 (21 days after landfall). Radiometric corrections (Katkovsky et al., 2018) and atmospheric scattering adjustments (Nazeer et al., 2014) were applied using ENVI 5.2, followed by false-colour composite generation in Erdas Imagine 2014.

2.4 Vegetation Health and Gap Dynamics Assessment

The Normalized Difference Vegetation Index (NDVI) was used to evaluate vegetation health, with NDVI thresholds categorizing dense (>0.6), open (0.2–0.6), and degraded (<0.2) mangrove classes (Meneses-Tovar, 2011; Nandi et al., 2020). NDVI values were derived for each site pre- and post-cyclone using ArcGIS 10.3.1, and changes were visualized through line graphs. Spatial pattern analysis was conducted using FRAGSTATS 4.2 to measure canopy gap dynamics and assess fragmentation patterns across the selected sites. Metrics such as the number of patches (NP), patch density (PD), largest patch index (LPI), landscape shape index (LSI), mean perimeter-area ratio (PARA_MN), patch area (AREA), perimeter (PERIM), shape index (SHAPE), and clumpiness (CLUMPY) were analysed (McGarigal and Marks, 1995; Nandi et al., 2020). These metrics revealed significant fragmentation patterns and vegetation transitions, providing insights into the canopy structure and its response to cyclonic impacts.

III. RESULT AND DISCUSSION

3.1 Result on Vegetation health dynamics

The analysis revealed a significant decline in vegetation health across the selected mangrove fringe areas in the Indian Sundarbans following the impact of Cyclone Bulbul, highlighting the fragility of these ecosystems under extreme climatic events. The cyclone, characterized by sustained wind speeds of up to 135 km/h and heavy rainfall, caused widespread damage to the mangrove canopy, with substantial reductions observed in NDVI metrics. The mean NDVI exhibited notable declines, with the highest reduction in North-Bakkhali (28.3%), followed by Shikarpur (24.69%), North-Mousuni (19.9%), Sibaloy (19.8%), and Dwarikanagar (15.7%) (Figure 3). These findings indicate severe vegetation thinning and stress, particularly in regions directly along the cyclone's trajectory (Figure 2 and 3). The maximum NDVI, indicative of the healthiest vegetation zones, also registered significant reductions, with Shikarpur experiencing the steepest decline (23.2%), followed by North-Bakkhali (21.4%) and North-Mousuni (Figure 3). Sibaloy exhibited the least reduction, suggesting comparatively lower canopy damage in this area. The spatial distribution of damage underscores the compounded impact of the cyclone's path and human interference, with North-Bakkhali emerging as the most devastated site due to its proximity to the cyclone's landfall and ongoing anthropogenic pressures.



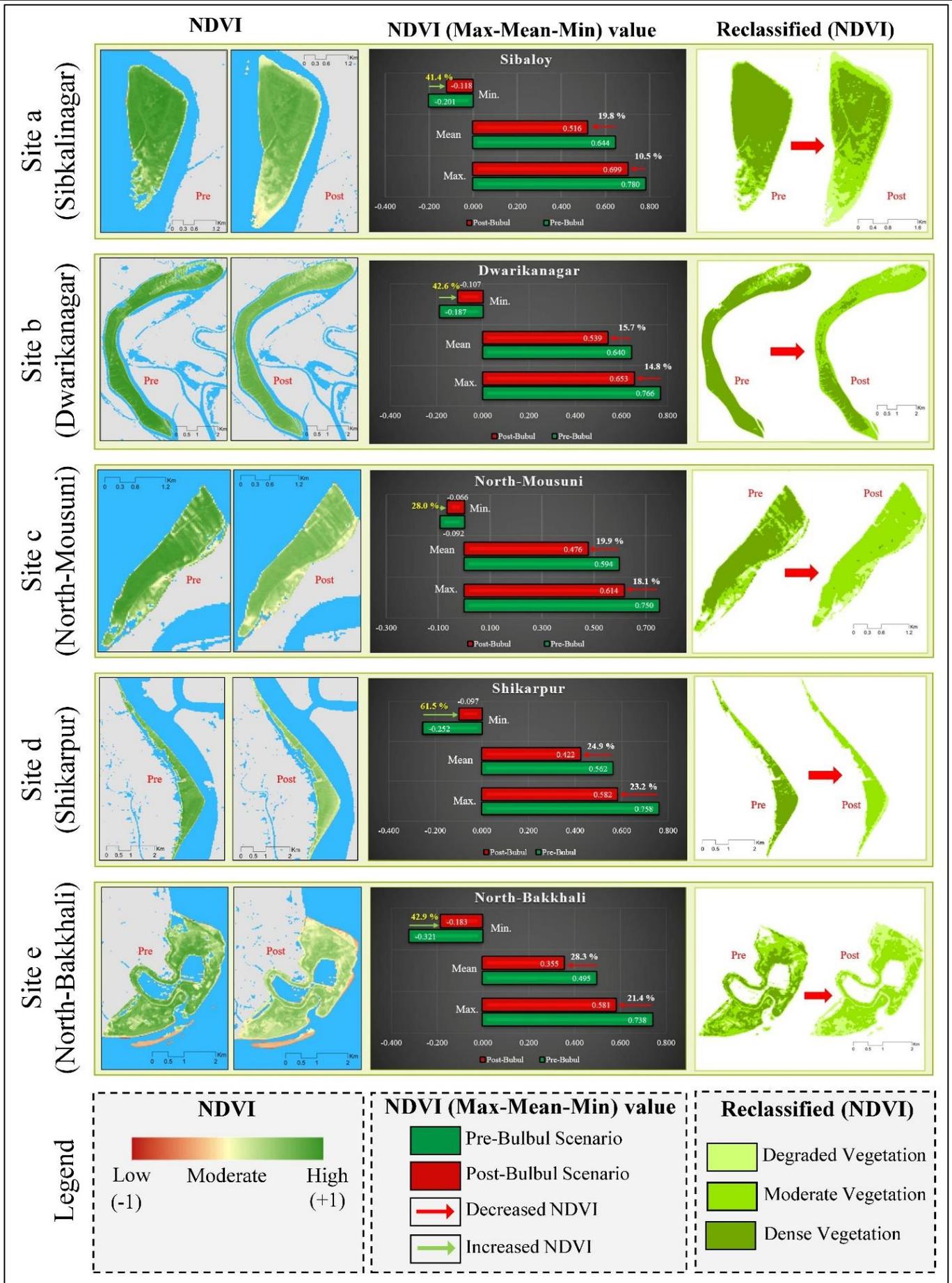


Figure 3: Cyclone Bulbul-Induced Changes in NDVI and Vegetation Cover Across Selected Sundarbans Mangrove Sites

Cyclone Bulbul's destructive force uprooted mangrove trees, stripped foliage, and inundated low-lying areas with saline water, exacerbating environmental stress and reducing vegetation health across the region. The decrease in minimum NDVI values further illustrates the widespread degradation of marginal vegetation zones, emphasizing the cyclone's extensive impact on even the less-healthy areas of the mangrove ecosystem (Figure 3 and 4). The findings also highlight a pattern of greater devastation in areas closer to the Bay of Bengal, reflecting the influence of storm surges and saltwater intrusion (Figure 4).

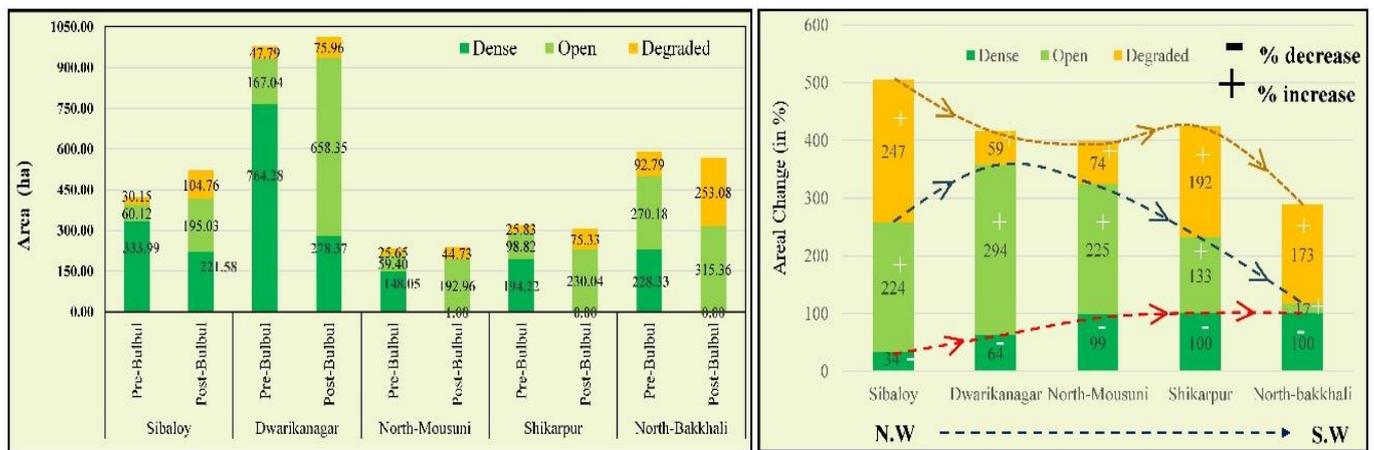


Figure 4: Pre- and Post-Cyclone Bulbul Changes in Mangrove Vegetation Cover and Area Dynamics

These environmental disturbances not only disrupt the ecological stability of the mangroves but also pose significant challenges to the livelihoods of local communities reliant on these forests for sustenance. This underscores the urgent need for targeted conservation and restoration efforts, incorporating climate-resilient management strategies to protect the mangroves of the Indian Sundarbans from future cyclonic events and anthropogenic pressures.

3.2 Result on Canopy gap dynamics

The analysis of canopy gaps across the study sites revealed severe fragmentation and canopy degradation caused by Cyclone Bulbul, significantly altering landscape metrics.

Table 1: Landscape Configuration and Fragmentation Metrics of Mangrove Classes Before and After Cyclone Bulbul

Study site	Landcover	Scenario	Total class area (CA)	Number of patches (NP)	Patch density (PD)	Landscape patch index (LPI)	Landscape shape index (LSI)	Mean perimeter-area ratio (PARAM)	Clumpiness (CLUMPY)
Sibaloy	Degraded	Pre-Bulbul	30.15	66	2.93	0.27	11.54	1073.34	0.38
		Post-Bulbul	104.76	24	1.07	4.4	7.48	1030.64	0.79
	Open	Pre-Bulbul	60.12	53	2.35	1.35	11.75	1001.65	0.55
		Post-Bulbul	195.03	38	1.69	7.62	9.76	1034.74	0.79
	Dense	Pre-Bulbul	333.99	12	0.53	14.56	2.99	859.38	0.96
		Post-Bulbul	221.58	15	0.67	9.72	6.3	1049.32	0.88
Dwarikanagar	Degraded	Pre-Bulbul	47.79	211	4.12	0.09	16.91	1211.22	0.26
		Post-Bulbul	75.96	229	4.48	0.72	15.41	1235.93	0.47

	Open	Pre-Bulbul	167.0 4	227	4.44	2.09	18.36	1188.47	0.57
		Post-Bulbul	658.3 5	32	0.63	10.83	10.32	998.28	0.87
	Dense	Pre-Bulbul	764.2 8	28	0.55	14.68	5.94	1017.04	0.94
		Post-Bulbul	278.3 7	95	1.86	4.22	8.86	1069.05	0.85
North-Mousuni	Degraded	Pre-Bulbul	25.65	70	5.44	0.35	10.74	1175.9	0.37
		Post-Bulbul	44.73	43	3.34	1.39	9.2	1157.21	0.6
	Open	Pre-Bulbul	59.4	46	3.57	1.52	12.13	1095.44	0.52
		Post-Bulbul	192.9 6	13	1.01	14.45	3.8	994.16	0.93
	Dense	Pre-Bulbul	148.0 5	17	1.32	11.25	4.94	1063.43	0.89
		Post-Bulbul	1.08	6	0.47	0.03	2.86	1166.67	0.23
Shikarpur	Degraded	Pre-Bulbul	25.83	128	4.36	0.06	14.15	1235.58	0.16
		Post-Bulbul	75.33	70	2.38	1.12	13.98	1076.53	0.52
	Open	Pre-Bulbul	98.82	81	2.76	1.4	13.46	1064.78	0.59
		Post-Bulbul	230.0 4	14	0.48	7.38	4.46	925.86	0.92
	Dense	Pre-Bulbul	194.2 2	31	1.06	4.89	6.09	959.28	0.88
		Post-Bulbul	<i>absent</i>						
North-Bakkhali	Degraded	Pre-Bulbul	92.79	203	8.76	0.32	18.52	1101.31	0.41
		Post-Bulbul	253.0 8	70	3.02	5.25	16.41	1013.64	0.66
	Open	Pre-Bulbul	270.1 8	94	4.05	4.32	19	1011.65	0.62
		Post-Bulbul	315.3 6	24	1.04	12.61	9.45	980.26	0.83
	Dense	Pre-Bulbul	228.3 3	42	1.81	2.76	12.69	988.42	0.74
		Post-Bulbul	<i>absent</i>						

In North-Mousuni, the transformation from dense to open and degraded patches was evident, with the total class area (CA) of dense patches reducing from 148.05 ha pre-cyclone to 1.08 ha post-cyclone. The number of patches (NP) for degraded areas in North-Mousuni increased, and clumpiness (CLUMPY) rose from 0.37 to 0.60, suggesting increased fragmentation but improved aggregation of degraded patches. In Shikarpur, a substantial shift from dense to open patches was observed, with dense patches decreasing in both NP and patch density (PD). The post-cyclone landscape showed an increase in CLUMPY for open patches from 0.52 to 0.59, reflecting higher spatial cohesion (Table 1). Degraded patches showed a significant increase in CA from 25.83 ha to 75.33 ha, alongside a reduction in mean perimeter-area ratio (PARA_MN) (Table 1), indicating smaller, more fragmented patches. North-Bakkhali displayed the most significant canopy disruption, with dense patches disappearing completely post-cyclone. Open patches expanded in area, with CA increasing from 270.18 ha to 315.36 ha, and LSI indicated a more complex patch configuration. The

clumpiness index for degraded areas rose sharply from 0.41 to 0.66, reflecting better connectivity within degraded patches. Overall, the transformation of dense mangrove canopies into open and degraded classes aligns with the cyclone's intensity and the pre-existing anthropogenic pressures. The metrics indicate that regions with less human interference, such as Sibaloy and Dwarikanagar, retained relatively higher canopy integrity, with minimal changes in CLUMPY and PARA_MN values (Table 1). These findings highlight the compounded effects of natural disasters and human activities on mangrove ecosystem fragmentation and degradation.

3.3 Discussion on cyclone impact and mangrove vulnerability

The combined impacts of Cyclone Bulbul, human activities, and physical stresses in the Indian Sundarbans highlight the intricate relationship between environmental degradation and socio-economic vulnerabilities. Mangrove ecosystems, which serve as vital protective barriers against cyclones and storm surges, are under significant strain from rising soil salinity, temperature fluctuations, changing precipitation patterns, and the increasing frequency of cyclonic events. These physical stressors exacerbate the already fragile state of mangroves, especially in regions like North-Bakkhali, Shikarpur, and North-Mousuni, which face additional pressures from shrimp farming, deforestation, and unsustainable resource extraction (Kar & Basu, 2023).

Rising soil salinity, driven by both saltwater intrusion from storm surges and the disruption of natural hydrological processes by embankments, severely impacts mangrove health. High salinity levels reduce vegetation density and canopy cover, leading to increased fragmentation. These fragmented patches are more susceptible to damage during cyclones, compromising their ecological functionality. In addition, temperature fluctuations and erratic rainfall patterns, attributed to climate change, further stress mangroves by disrupting seed germination and growth cycles, reducing their capacity for natural regeneration (Mondal et al., 2022).

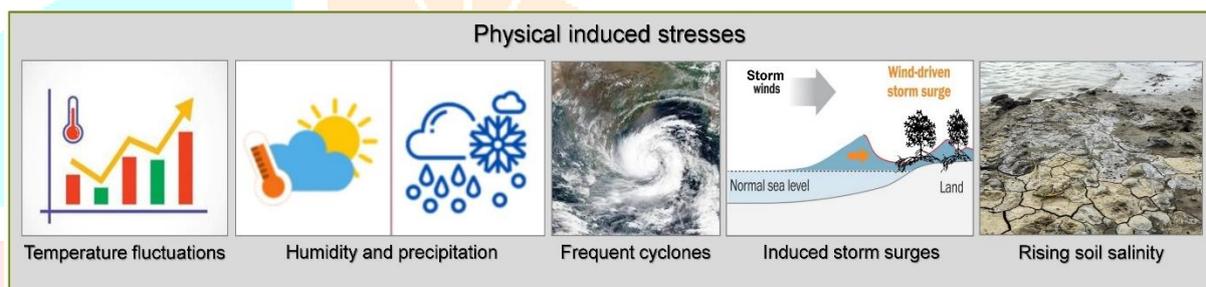


Figure 5: Key physical stressors impacting coastal ecosystems

The socio-economic consequences of mangrove degradation are profound. Communities that rely on mangroves for timber, honey, fish, and fuelwood face diminishing resources, exacerbating poverty and reducing resilience to cyclones. The loss of natural storm buffers increases vulnerability to flooding and erosion, while saltwater intrusion and degraded agricultural land lead to reduced crop yields and food insecurity. The damage to housing and infrastructure, compounded by rising soil salinity and frequent cyclones, forces many families to migrate in search of alternative livelihoods, further destabilizing the local socio-economic structure (Kar & Basu, 2023).

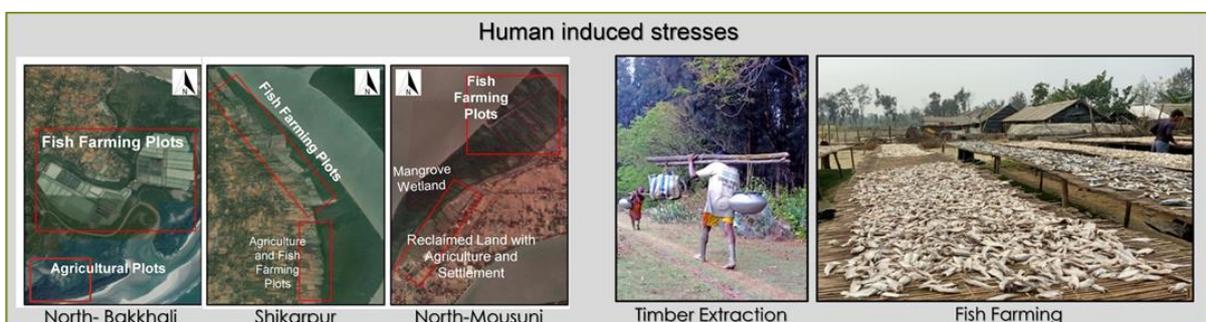


Figure 6: Anthropogenic stressors impacting mangrove ecosystems

Physical stressors also amplify the challenges posed by human-made structures like embankments and dikes. Designed to protect agricultural land, these structures disrupt sediment deposition and freshwater flows, worsening waterlogging and salinity. This weakens mangrove resilience and reduces their capacity to recover from cyclonic events, creating a feedback loop where ecological and socio-economic vulnerabilities reinforce each other (Mondal et al., 2022). To break this cycle, an integrated approach is essential. Restoring hydrological connectivity by modifying embankments and promoting natural sediment deposition can

mitigate salinity and support mangrove health. Afforestation with salinity-tolerant, native mangrove species can help restore degraded areas, while sustainable management practices, such as restricting shrimp farming in sensitive zones, can reduce anthropogenic pressures. Addressing the physical stressors, such as through the development of heat- and salinity-resistant mangrove species, is also critical to building ecosystem resilience (Kar & Basu, 2023). Community engagement is central to these efforts. Empowering local populations to participate in conservation activities, such as mangrove planting and monitoring, can foster stewardship while providing sustainable livelihoods. Enhancing disaster preparedness through improved early warning systems, cyclone shelters, and eco-friendly infrastructure can mitigate the socio-economic impacts of future cyclones. Linking conservation efforts with socio-economic development, such as promoting eco-tourism and non-timber forest product (NTFP) markets, can balance ecological restoration with economic growth.

IV. CONCLUSION

The degradation of mangrove ecosystems in the Sundarbans, driven by the combined effects of physical stressors and human-induced activities, poses severe ecological and socio-economic challenges. The diminishing health of these critical ecosystems undermines their capacity to serve as natural buffers against climate-induced disasters, thereby heightening the vulnerability of local communities. Addressing these issues requires an integrated approach that prioritizes ecological restoration through sustainable management practices, promotes alternative livelihoods to reduce dependency on mangroves, and enhances disaster preparedness and risk reduction strategies. Such comprehensive efforts are essential for ensuring the long-term resilience of both the mangrove ecosystems and the communities that rely on their services (Mondal et al., 2022; Kar & Basu, 2023).

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