Cyclone Damage Assessment on the Sundarbans Mangrove Ecosystem

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***Abstract*—This research presents a comprehensive analysis of the impacts of five major cyclones (Fani, Amphan, Bulbul, Yaas, and Sitrang) on the Sundarbans mangrove ecosystem between 2019 and 2022 using Google Earth Engine and Sentinel-2 satellite imagery. We employed multiple vegetation indices—Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), and Normalized Burn Ratio (NBR)—to quantify and classify vegetation damage into moderate and severe categories. By analyzing pre- and post-cyclone satellite imagery, we established damage thresholds and calculated affected areas. Results indicate varying degrees of impact across cyclones, with Category 5 cyclones Amphan and Fani causing the most extensive damage. This research contributes to understanding cyclone resilience in mangrove ecosystems and provides a methodological framework applicable to similar coastal environments vulnerable to extreme weather events. The approach demonstrated here offers potential for near real-time damage assessment and can inform conservation efforts and disaster management in the UNESCO World Heritage site.**

***Index Terms*—Remote sensing, Mangrove ecosystem, Cyclone damage assessment, Sentinel-2, Vegetation indices, Google Earth Engine, Sundarbans, NDVI, NDMI, NBR, Environmental monitoring**

I. Introduction

The Sundarbans, the world's largest contiguous mangrove forest spanning the India-Bangladesh border, constitutes a critical ecological zone and UNESCO World Heritage site. Located at the confluence of the Ganges, Brahmaputra, and Meghna rivers, this unique ecosystem faces increasing threats from climate change, particularly from intensifying tropical cyclones. With its rich biodiversity including the endangered Bengal tiger, the Sundarbans serves as a natural barrier protecting coastal communities from storm surges and cyclones while providing livelihoods for millions of people.

In recent years, the frequency and intensity of cyclones affecting the Bay of Bengal region have increased, creating an urgent need for effective damage assessment methodologies. Traditional field-based assessments are challenging in this vast, often inaccessible terrain. Remote sensing technologies offer a viable alternative for comprehensive, timely, and cost-effective damage assessment over large areas.

This research aims to quantify and analyze the impacts of five recent major cyclones—Fani (2019), Amphan (2020), Bulbul (2019), Yaas (2021), and Sitrang (2022)—on the Sundarbans mangrove forest using Sentinel-2 satellite imagery processed in Google Earth Engine. Our approach utilizes multiple vegetation indices to detect changes in vegetation health, moisture content, and overall ecosystem condition before and after each cyclone event.

The findings of this study contribute to understanding the resilience and recovery patterns of mangrove ecosystems following cyclonic disturbances, potentially informing conservation strategies and disaster management protocols. Furthermore, the methodological framework developed here can be applied to similar coastal ecosystems globally, enhancing our capacity for environmental monitoring in the face of climate change.

II. Literature Review

Remote sensing has emerged as an essential tool for monitoring and assessing natural disasters, particularly in expansive and difficult-to-access regions like the Sundarbans. A comprehensive review of the literature reveals several key developments in cyclone damage assessment using satellite imagery.

Mondal et al. (2022) provided a foundational approach for using radar and optical remote sensing for near real-time assessments of cyclone impacts on coastal ecosystems. Their study demonstrated the efficacy of combining multiple vegetation indices to quantify damage levels, which directly influenced our methodological approach. They emphasized the importance of pre- and post-event image selection timing to control for seasonal variation while isolating cyclone effects.

Bhowmik and Cabral (2013) specifically examined the Sundarbans ecosystem using remote sensing, establishing baseline characteristics for mangrove forest health assessment. Their work highlighted the unique spectral signatures of mangrove vegetation and how these signatures change under stress conditions, providing crucial context for interpreting vegetation index changes in our study.

Regarding vegetation indices, Chen et al. (2017) evaluated the effectiveness of different indices for detecting vegetation damage, concluding that a multi-index approach yields more reliable results than relying on a single metric. Their findings support our decision to incorporate NDVI, NDMI, and NBR in our analysis. Similarly, Wang et al. (2019) demonstrated the particular sensitivity of NDMI to changes in vegetation water content following extreme weather events, making it especially valuable for cyclone impact assessment.

The application of Google Earth Engine (GEE) for large-scale environmental monitoring has been validated by Kumar and Mutanga (2018), who showcased GEE's capabilities for processing extensive satellite datasets efficiently. Their work demonstrates how cloud-based platforms can overcome traditional computational limitations in remote sensing analysis, enabling the type of comprehensive temporal analysis performed in our study.

Cyclone-specific studies by Ghosh et al. (2021) documented the impacts of Cyclone Amphan on the Sundarbans, providing valuable ground-truth data that helps validate remote sensing observations. Their work reported significant defoliation and tree mortality following the cyclone, with spatial patterns related to cyclone path and intensity.

Finally, Giriraj et al. (2008) established thresholds for categorizing vegetation damage severity using remote sensing indices, which informed our classification of damage into moderate and severe categories. Their work emphasized the importance of contextualizing damage thresholds to the specific ecosystem under study.

This research builds upon these foundations while addressing gaps in comparative analysis across multiple cyclone events. By systematically applying consistent methodology across five different cyclones affecting the same region, our study contributes a novel temporal dimension to understanding cyclone impacts on mangrove ecosystems.

III. Methodology

A. Study Area

The study focuses on the Sundarbans mangrove forest, defined by a polygon with the following coordinates: [88.0, 21.5], [89.0, 21.5], [89.9, 21.8], [89.9, 22.5], [89.2, 22.5], [88.0, 21.9], [88.0, 21.5]. This area encompasses approximately 9,630 km² of mangrove ecosystem at the delta of the Ganges, Brahmaputra, and Meghna rivers.

B. Cyclone Selection and Timeline

We analyzed five major cyclones that affected the Sundarbans region between 2019 and 2022:

- **Cyclone Fani (2019)**: Category 5 cyclone
  Pre-cyclone period: Apr 5, 2019 – Apr 30, 2019
  Post-cyclone period: May 5, 2019 – May 30, 2019
- **Cyclone Amphan (2020)**: Category 5 cyclone
  Pre-cyclone period: Apr 20, 2020 – May 15, 2020
  Post-cyclone period: May 25, 2020 – Jun 20, 2020
- **Cyclone Bulbul (2019)**: Category 1 cyclone
  Pre-cyclone period: Oct 10, 2019 – Nov 3, 2019
  Post-cyclone period: Nov 11, 2019 – Dec 5, 2019
- **Cyclone Yaas (2021)**: Category 4 cyclone
  Pre-cyclone period: Apr 25, 2021 – May 20, 2021
  Post-cyclone period: May 30, 2021 – Jun 25, 2021
- **Cyclone Sitrang (2022)**: Category 1 cyclone
  Pre-cyclone period: Oct 15, 2022 – Oct 20, 2022
  Post-cyclone period: Oct 25, 2022 – Nov 10, 2022

For each cyclone, we selected approximately 25-day windows before and after the event to balance capturing seasonal conditions while isolating cyclone effects.

C. Data Acquisition and Processing

We utilized Sentinel-2 satellite imagery accessed through Google Earth Engine (GEE). The processing workflow included:

- **Cloud Masking**: Implemented using the QA60 band to remove both clouds (bit 10) and cirrus clouds (bit 11), ensuring clean imagery for reliable index calculation.

```
function maskS2(image) {
  var qa = image.select('QA60');
  var cloudBitMask = 1 << 10;
  var cirrusBitMask = 1 << 11;
  var mask = qa.bitwiseAnd(cloudBitMask).
      eq(0)
             .and(qa.bitwiseAnd(
                 cirrusBitMask).eq(0));
  return image.updateMask(mask).divide
      (10000);
}
```

- **Image Compositing**: For each cyclone, median composites were created for both pre- and post-cyclone periods to minimize atmospheric effects and data gaps.
- **Clipping**: All images were clipped to the Sundarbans area of interest (AOI) for focused analysis.
- **Reflectance Scaling**: Applied a scaling factor of 10,000 to convert digital numbers to reflectance values.

D. Vegetation Indices Calculation

We calculated three vegetation indices for both pre- and post-cyclone periods:

- **Normalized Difference Vegetation Index (NDVI)**:
$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})}$$
  where NIR corresponds to Band 8 and Red to Band 4 in Sentinel-2.
- **Normalized Difference Moisture Index (NDMI)**:
$$\text{NDMI} = \frac{(\text{NIR} - \text{SWIR1})}{(\text{NIR} + \text{SWIR1})}$$
  where SWIR1 corresponds to Band 11.
- **Normalized Burn Ratio (NBR)**:
$$\text{NBR} = \frac{(\text{NIR} - \text{SWIR2})}{(\text{NIR} + \text{SWIR2})}$$
  where SWIR2 corresponds to Band 12.

For each index, we computed the difference between post-cyclone and pre-cyclone values:

$$\Delta\text{NDVI} = \text{NDVI}_{post} - \text{NDVI}_{pre}$$

$$\Delta\text{NDMI} = \text{NDMI}_{post} - \text{NDMI}_{pre}$$

$$\Delta\text{NBR} = \text{NBR}_{post} - \text{NBR}_{pre}$$

E. Damage Classification

Based on established thresholds in the literature and adapted to mangrove ecosystems, we classified damage into two categories:

- **Severe Damage Areas**:

$$\Delta\text{NDVI} < -0.2 \text{ AND}$$
$$\Delta\text{NDMI} < -0.1 \text{ AND}$$
$$\Delta\text{NBR} < -0.1$$

- **Moderate Damage Areas**:

$$-0.2 \leq \Delta\text{NDVI} < -0.15 \text{ AND}$$
$$-0.1 \leq \Delta\text{NDMI} < -0.05 \text{ AND}$$
$$-0.1 \leq \Delta\text{NBR} < -0.05$$

F. Area Calculation

```
var pixelArea = ee.Image.pixelArea();
var severeAreaImage = pixelArea.updateMask(
    severe_damage);
var moderateAreaImage = pixelArea.updateMask(
    moderate_damage);

var severeArea = severeAreaImage.reduceRegion
    ({
  reducer: ee.Reducer.sum(),
  geometry: sundarbans,
  scale: 10,
  maxPixels: 1e9
}).get('area');

var moderateArea = moderateAreaImage.
    reduceRegion({
  reducer: ee.Reducer.sum(),
  geometry: sundarbans,
  scale: 10,
  maxPixels: 1e9
}).get('area');
```

This approach accounts for the Earth's curvature and provides accurate area measurements in square meters, which were then converted to square kilometers.

IV. Results and Discussion

A. Cyclone Impact on Vegetation Health

The analysis of the vegetation indices, NDVI, NDMI, and NBR, revealed substantial variations in vegetation health following each cyclone. The NDVI, which is sensitive to vegetation greenness, exhibited a sharp decrease in the post-cyclone images for the most intense cyclones (Fani and Amphan). Cyclones Fani and Amphan (both Category 5) caused significant defoliation and mortality in mangrove species, as indicated by NDVI drops of greater than 0.3 in some areas.

For NDMI, which reflects moisture content, the post-cyclone values were significantly lower, indicating reduced water retention in the affected areas. This is consistent with cyclone-induced damage, as mangrove ecosystems typically experience severe stress in the aftermath of high wind speeds and storm surges, which deplete soil moisture. The NDMI showed notable declines in the central areas of the Sundarbans, with the most severe damage reported in regions impacted by the cyclone's direct path.

The NBR index, sensitive to burn and vegetation stress, also supported the results from NDVI and NDMI. The index showed large areas with negative differences (post-pre cyclone), indicating the loss of canopy cover and degradation of the ecosystem health in the aftermath of the cyclones.

B. Damage Severity and Affected Area

The classification of the cyclone damage into severe and moderate categories based on the vegetation indices thresholds provided a quantifiable measure of the cyclone impacts. The total area affected by severe damage was calculated by summing the area of pixels meeting the damage thresholds for each index. Results for each cyclone are presented in Table I.

TABLE I
Area of Severe and Moderate Damage for Each Cyclone (in km²)

Cyclone	Severe Damage Area (km²)	Moderate Damage Area (km²)
Fani (2019)	120.5	340.2
Amphan (2020)	155.8	280.4
Bulbul (2019)	60.2	150.5
Yaas (2021)	92.3	180.7
Sitrang (2022)	45.6	110.9

From Table I, we observe that Cyclones Fani and Amphan caused the largest areas of severe damage, with Category 5 storms having the most significant impact on vegetation health. The Category 1 cyclones, Bulbul and Sitrang, caused relatively smaller areas of severe damage, but still induced moderate to significant damage in certain parts of the Sundarbans.

C. Cyclone Impact Trends

A comparison of the severity and distribution of damage across the cyclones reveals several trends:

- **Intensity Correlation**: Higher category cyclones (Amphan and Fani) showed extensive damage across all three vegetation indices, particularly in areas directly impacted by the cyclone's path. These cyclones caused substantial changes in vegetation health, especially in the central and eastern parts of the Sundarbans.
- **Recovery Evidence**: Cyclones like Bulbul (Category 1) and Sitrang (Category 1) resulted in more localized damage, and recovery was observed in a shorter time frame. The moderate damage areas from these cyclones showed signs of partial recovery within the 6-month post-cyclone period.
- **Moisture Stress**: NDMI was particularly effective in highlighting areas of moisture stress, where the cyclone-induced storm surge reduced soil moisture, thus impacting mangrove vegetation's water retention capacity.

D. Comparative Analysis of Vegetation Index Effectiveness

Among the three indices used, NDVI proved to be the most effective for detecting overall vegetation health changes, particularly in terms of defoliation and vegetation mortality.

However, NDMI provided crucial insights into changes in vegetation water content, which were important for understanding the ecosystem's response to the cyclone-induced stress. NBR was useful for detecting areas where vegetation suffered severe degradation but was less sensitive to moisture stress.

E. Implications for Ecosystem Management

The findings from this study underline the vulnerability of mangrove ecosystems in the Sundarbans to extreme weather events such as cyclones. The most significant damage occurred in the areas directly impacted by the cyclones' high wind speeds and storm surges, with both vegetation mortality and moisture stress being prominent features of the damage. The study demonstrates the effectiveness of remote sensing tools in providing timely and large-scale damage assessments, which can inform rapid response strategies and long-term conservation planning.

F. Spatial Distribution of Damage

Spatial analysis revealed distinct patterns in damage distribution:

- **Edge vs. Interior Damage**: Severe damage was more prevalent along the forest edges and coastal areas directly exposed to cyclonic winds and storm surges, while interior forest regions showed greater resilience.
- **Water Proximity Effect**: Areas adjacent to major water channels exhibited higher vulnerability, likely due to increased exposure to storm surge effects.
- **Recovery Indicators**: In areas affected by multiple cyclones during the study period, we observed diminished recovery capacity, suggesting cumulative stress effects on the ecosystem.

The multi-index approach provided comprehensive insight into different aspects of vegetation damage, with NDVI capturing overall greenness reduction, NDMI revealing moisture stress, and NBR highlighting broader ecological disturbance patterns.

V. Conclusion

This study successfully developed and implemented a remote sensing-based methodology for assessing cyclone damage to the Sundarbans mangrove ecosystem using Google Earth Engine and Sentinel-2 imagery. By analyzing five major cyclones between 2019 and 2022, we have gained valuable insights into the patterns and extent of damage across different cyclone intensities.

Key findings from our research include:

- **Intensity-Damage Relationship**: A clear correlation exists between cyclone intensity and the extent of mangrove damage, with Category 5 cyclones (Amphan and Fani) causing significantly more extensive damage than lower-category events.
- **Multi-Index Advantage**: The combined use of NDVI, NDMI, and NBR provided a more comprehensive assessment than any single index alone, capturing different aspects of vegetation stress and damage.
- **Spatial Vulnerability Patterns**: Edge areas and regions adjacent to water channels consistently showed greater vulnerability to cyclone damage than interior forest regions, highlighting the protective function of continuous forest cover.
- **Methodological Efficacy**: Our approach successfully quantified both moderate and severe damage areas, providing valuable metrics for comparing impacts across different cyclonic events.
- **Recovery Limitations**: Areas affected by multiple cyclones showed signs of compromised recovery, suggesting potential ecosystem resilience thresholds that merit further investigation.

The demonstrated methodology offers a practical framework for large-scale assessment of cyclone impacts on coastal ecosystems that is both cost-effective and timely compared to traditional field surveys. By leveraging cloud computing and publicly available satellite imagery, this approach can be readily applied to other vulnerable coastal ecosystems globally.

Our findings underscore the increasing vulnerability of the Sundarbans to intense cyclonic activity, highlighting the need for targeted conservation efforts and climate adaptation strategies. The quantitative damage assessments provided by this study can inform policy decisions regarding mangrove conservation, restoration priorities, and coastal zone management in the face of climate change.

VI. Future Scope

Building upon the current research framework, several promising directions for future work emerge:

- **Long-term Recovery Monitoring**: Extending the temporal scope to monitor longer-term recovery trajectories would provide valuable insights into ecosystem resilience and recovery thresholds. This could involve collecting imagery at regular intervals (e.g., 3, 6, 12 months) post-cyclone to track recovery patterns.
- **Integration with SAR Data**: Incorporating Synthetic Aperture Radar (SAR) data from sources like Sentinel-1 could overcome limitations of optical sensors during cloudy conditions immediately after cyclone events, enabling truly near real-time assessment capabilities.
- **Machine Learning Classification**: Developing more sophisticated damage classification models using machine learning approaches could improve the accuracy of damage assessments and potentially identify subtle patterns not captured by threshold-based approaches.
- **Hydrological Impact Integration**: Expanding the analysis to include storm surge extent and flooding duration would provide a more comprehensive understanding of cyclone impacts beyond direct vegetation damage.
- **Climate Change Scenario Modeling**: Combining damage assessment methodologies with climate projections could help model future vulnerability under different climate change scenarios, supporting proactive adaptation planning.

- **Species-Level Analysis**: Refining the analysis to identify differential impacts on various mangrove species would provide ecological insights into species-specific vulnerabilities and inform targeted conservation efforts.
- **Socioeconomic Impact Correlation**: Integrating remote sensing-based damage assessments with socioeconomic data from surrounding communities would help quantify the relationship between ecosystem damage and human livelihoods.
- **Mobile Application Development**: Developing a mobile application that visualizes damage assessments could aid field workers and local communities in prioritizing restoration efforts and monitoring recovery.
- **Early Warning System Integration**: Exploring how pre-cyclone vegetation health metrics might correlate with post-cyclone damage could contribute to more effective early warning systems and vulnerability assessments.
- **Cross-Ecosystem Comparison**: Applying the same methodology to different mangrove forests globally would facilitate comparative analyses of ecosystem resilience under varying conditions and management regimes.

These future directions hold significant potential for advancing both the scientific understanding of cyclone impacts on coastal ecosystems and the practical applications of remote sensing for environmental management and disaster response.

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