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Spatio-Temporal NDVI dynamics and cyclone impact assessment (2020-2024): Balukhanda wildlife Sanctuary, Puri, Odisha

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Abstract
This study investigates the spatio-temporal dynamics of vegetation and the impacts of cyclonic disturbances within the Balukhanda Wildlife Sanctuary (BKWLS), a fragile coastal ecosystem along the Puri-Konark marine corridor of Odisha, India, for the period 2020-2024. Multi-temporal satellite imagery from Landsat and Sentinel sensors was analyzed to derive the Normalized Difference Vegetation Index (NDVI) and assess seasonal vegetation patterns. During the pre-monsoon season (March-June), NDVI values were generally lower, reflecting elevated vegetation stress due to high temperatures, limited rainfall, and reduced soil moisture. *Casuarina equisetifolia* plantations exhibited moderate NDVI levels, indicating relative resilience to drought and salinity, whereas scrub and dune vegetation showed lower greenness. The study further highlights the influence of major cyclones, including Amphan (2020) and Yaas (2021), on canopy structure and vegetation cover, with NDVI-based change detection revealing zones of temporary degradation and subsequent regeneration. These results underscore the ecological sensitivity of the sanctuary to seasonal climatic variations and extreme weather events, emphasizing the importance of continuous monitoring to inform adaptive management strategies for coastal forest conservation and biodiversity protection.

Keywords: Cyclone, NDVI, saptio-temporal, wilde life santuray

1. Introduction

Nursing encompasses autonomous and collaborative care of individuals of all ages, families, groups and communities, sick or well and in all settings. Nursing includes the promotion of health, prevention of illness, and the care of ill, disabled and dying people. Advocacy, promotion of a safe environment, research, participation in shaping health policy and in patient and health systems management, and education are also key nursing roles [1].

Balukhanda-Konark Wildlife Sanctuary, stretching along the Puri-Konark marine drive in Odisha, is a fragile coastal ecosystem composed of casuarina plantations, sand dunes, scrub forests, and coastal vegetation. This sanctuary plays a vital role in coastal protection, biodiversity conservation, and eco-tourism.

Balukhanda-Konark Wildlife Sanctuary, situated along the Puri-Konark marine drive in Odisha, represents a fragile yet ecologically significant coastal ecosystem comprising casuarina plantations, sand dunes, scrub forests, and diverse coastal vegetation. The sanctuary serves as a natural barrier against coastal erosion, protecting nearby human settlements while maintaining vital biodiversity and supporting eco-tourism initiatives that enhance local livelihoods and environmental awareness (Forest Department, Government of Odisha, 2023) [4]. Several studies have highlighted the sanctuary's ecological importance and vulnerability to natural disturbances. For instance, Mishra *et al*., (2021) [7] used Landsat imagery to analyze vegetation loss and shoreline changes following Cyclone Fani, revealing extensive damage to coastal forests. Similarly, Nandi *et al.*, (2020) [8] observed significant short-term landscape disturbances in the area due to cyclonic impacts. Research by Kumari *et al.*, (2023) [5] emphasized the need for mitigation strategies to protect such wildlife sanctuaries from immediate cyclone-induced damages. Recent modeling by Mishra *et al.*, (2025) [6] projected future shoreline dynamics and land use/land cover changes using machine learning, underlining the sanctuary's sensitivity to climatic and anthropogenic pressures. Avifaunal studies by Palei *et al*., (2020) [9] documented the diverse bird species and their breeding statuses, indicating the site's role as an essential habitat for coastal and migratory species. Additionally, Rajendra (2024) [10] recorded new marine hetero-branch species from within the sanctuary area, further demonstrating its rich and varied biodiversity. Collectively, these studies reinforce the significance of Balukhanda-Konark Wildlife Sanctuary as a critical zone for coastal protection, biodiversity conservation, and scientific research in eastern India.

Due to its location on the Bay of Bengal coast, the sanctuary is highly exposed to cyclones, storm surges, saltwater intrusion, and anthropogenic pressures. Vegetation monitoring using the Normalized Difference Vegetation Index (NDVI) helps assess the health, stress, and regeneration capacity of this ecosystem.

This study examines NDVI variations (2020-2024) across Pre-Monsoon (Mar-Jun) and Post-Monsoon (Sep-Dec) seasons, and evaluates the impact of cyclones on vegetation greenness.

The present study is designed with the primary objective of examining the spatio-temporal dynamics of vegetation within the Balukhanda-Konark Wildlife Sanctuary. Specifically, it aims to analyze the seasonal Normalized Difference Vegetation Index (NDVI) trends from 2020 to 2024 to understand fluctuations in vegetation health and density across different seasons. Furthermore, the study seeks to assess the impact of cyclonic disturbances on vegetation cover, as such events frequently alter the ecological stability of coastal landscapes. By integrating multi-temporal satellite data and geospatial analysis, the research also intends to identify distinct patterns of vegetation stress and post-disturbance regeneration within this fragile coastal ecosystem. Overall, these objectives are directed toward evaluating the ecological resilience of the sanctuary and contributing valuable insights for sustainable coastal forest management and biodiversity conservation in the face of increasing climatic variability.

2. Materials and Methods

This study adopted an integrated remote sensing and GIS-based approach to analyze vegetation dynamics, cyclone-induced stress, and post-disturbance regeneration patterns within the Balukhanda-Konark Wildlife Sanctuary (BKWLS) during 2020-2024. Multi-temporal satellite datasets were utilized to derive the Normalized Difference Vegetation Index (NDVI), which effectively represents vegetation greenness and health (Mishra *et al*., 2021; Nandi *et al*., 2020) [7,8]. Landsat-8 Operational Land Imager (OLI), were acquired from the United States Geological Survey (USGS) and Copernicus Open Access Hub platforms, respectively. These datasets, known for their moderate spatial resolution (10-30 m) and high temporal frequency, were selected to ensure consistency in long-term trend analysis (Mishra *et al*., 2025) [6].

2.1 Seasonal Classification and Image Processing

The temporal dataset was classified into two distinct seasonal periods pre-monsoon (March-June), representing dry and hot conditions with low soil moisture, and post-monsoon (September-December), representing the phase of high rainfall, soil moisture recharge, and vegetation regrowth (Kumari *et al*., 2023) [5]. Cloud-free images from these seasons were selected for each study year. Preprocessing operations, including radiometric calibration, atmospheric correction, and geometric rectification, were performed using ERDAS Imagine 2020 and ArcGIS Pro 3.0 to enhance image accuracy.

2.2 Cyclone Data and Impact Analysis

To assess the influence of major tropical cyclones on vegetation health, data were collected from official reports of the India Meteorological Department (IMD) for Cyclone Amphan (2020), Cyclone Yaas (2021), Cyclone Mocha (2023), and Cyclone Remal (2024). Cyclone track, intensity, and wind-speed data were integrated into the GIS environment to delineate impact zones across the sanctuary (Nandi *et al*., 2020) [8]. Pre- and post-cyclone NDVI composites were compared to quantify vegetation loss and regeneration. NDVI maxima and minima were extracted seasonally and annually to analyze inter-annual trends in vegetation performance and ecosystem recovery (Mishra *et al*., 2025) [6].

2.3 Data Validation and Statistical Analysis

Ground reference data and vegetation records from the Forest Department, Government of Odisha, along with published ecological assessments on bird diversity and habitat quality, were used for validation (Palei *et al*., 2020; Rajendra, 2024) [9, 10]. Statistical analyses, including correlation, temporal trend analysis, and mean NDVI variation to interpret the relationship between vegetation condition and cyclonic disturbances.

The methodological framework, therefore, integrates satellite remote sensing, seasonal NDVI classification, and cyclone impact modeling to evaluate vegetation dynamics, ecological resilience, and regeneration capacity of the Balukhanda-Konark Wildlife Sanctuary.

- **Satellite Data:** Landsat / Sentinel imagery processed for NDVI values.
- **Seasonal Classification**
- **Pre-Monsoon (Mar-Jun):** Dry, hot, low soil moisture.
- **Post-Monsoon (Sep-Dec):** High rainfall, soil moisture recharge, vegetation regrowth.
- **Cyclone Records:** IMD cyclone reports (Amphan 2020, Yaas 2021, Mocha 2023, Remal 2024).
- **Analysis:** NDVI maxima and minima extracted; compared seasonally and annually.

2.4 Study Area: Balukhand Wildlife Sanctuary, Puri, Odisha

The Balukhand Wildlife Sanctuary, also referred to as Balukhand-Konark Wildlife Sanctuary, is a coastal protected area located along the Bay of Bengal coast in Puri district, Odisha, India (21.87°N, 86.09°E) (Bal *et al*., 2023) [1]. The sanctuary was established in 1984 and spans approximately 87 km², encompassing a variety of ecosystems including sandy beaches, coastal dunes, casuarina plantations, and sparse forest patches (Bal *et al*., 2023; e-Planet, 2018) [1, 3].

Ecologically, the sanctuary supports rich biodiversity, including mammals such as spotted deer (*Axis axis*), blackbuck (*Antilope cervicapra*), jungle cat (*Felis chaus*), hyena (*Hyaena hyaena*), and jackal (*Canis aureus*), as well as diverse bird populations and reptiles (Bal *et al*., 2023; e-Planet, 2018) [1, 3]. Olive Ridley sea turtles (Lepidochelys olivacea) utilize the coastal beaches of the sanctuary for nesting during breeding seasons (Bal *et al*., 2023) [1].

Recent conservation efforts have focused on habitat restoration and species reintroduction. For instance, blackbucks were reintroduced into the sanctuary in 2024 following local extirpation due to habitat loss and human disturbance (Times of India, 2023) [12]. Despite these measures, ecological studies indicate a decline in dense vegetation cover from 41.8% in 1993 to 37.1% in 2023, largely attributed to anthropogenic pressures and environmental stressors (Times of India, 2023) [12].

The sanctuary is also notable for its avian diversity. A one-year survey (February 2017-January 2018) recorded 230 bird species, including 113 resident species, 100 winter visitors, and 12 passage migrants, highlighting its importance as a coastal bird habitat (e-Planet, 2018) [3]. The area is accessible via the Puri-Konark Marine Drive and provides opportunities for eco-tourism, nature walks, and community-based forest management initiatives (Community Conserved Areas, 2023) [2].

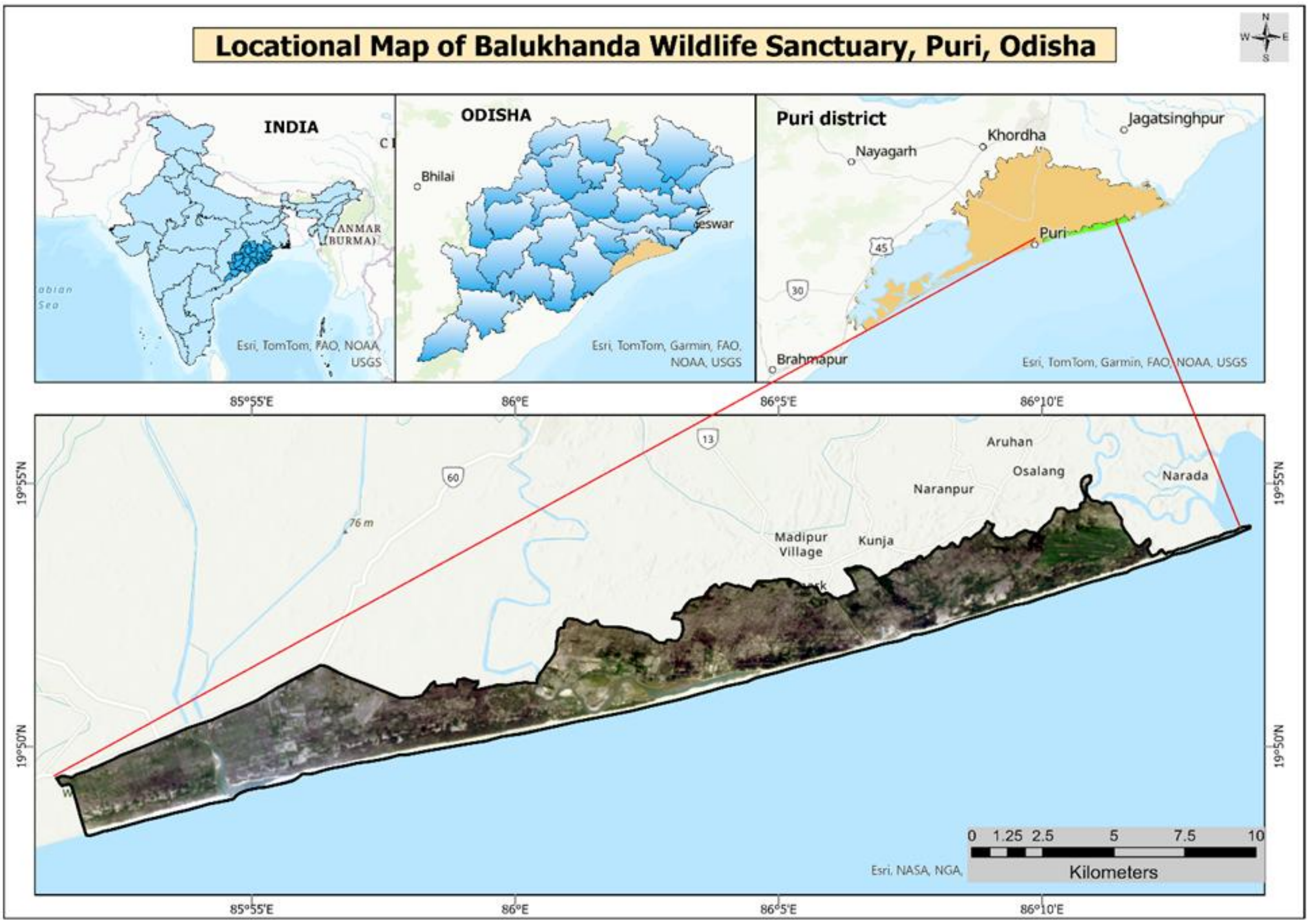

Fig 1: Location of the Study area

2.5 Calculation of Normalized Difference Vegetation Index (NDVI)

One of the most common and widely used remote sensing products is the vegetation index, which quantifies vegetation by analyzing the spectral reflectance of the Earth's surface captured by satellite sensors. The Normalized Difference Vegetation Index (NDVI) is defined as the difference between the near-infrared (NIR) and red (RED) reflectance, normalized by their sum, and is expressed as follows:

$$NDVI=NIR-RED/NIR+RED$$

NDVI values range from -1 to +1, where higher positive values indicate dense and healthy vegetation, values near zero indicate bare soil or sparse vegetation, and negative values correspond to water or non-vegetated surfaces (Shahfahad *et al.*, 2021) [11].

3. Results and Discussion

3.1 Pre-Monsoon Vegetation Status

The Pre-Monsoon NDVI map illustrates vegetation conditions in Balukhanda-Konark Wildlife Sanctuary during the Pre-Monsoon season (March-June) for the study period 2020-2024. This period represents the late dry season when vegetation stress is typically higher due to reduced rainfall and elevated temperatures.

The Pre-Monsoon NDVI analysis for the period 2020-2024 reflects a distinct seasonal pattern of vegetation stress within the Balukhanda-Konark Wildlife Sanctuary (BKWLS). During this dry season, typically extending from March to June, vegetation cover exhibited lower NDVI values, indicating reduced chlorophyll activity and limited photosynthetic performance. This seasonal decline corresponds to the combined effects of elevated surface temperatures, declining soil moisture, and minimal precipitation, which collectively constrain plant growth and canopy density. Similar observations have been reported in other coastal forest ecosystems, where pre-monsoon aridity leads to temporary vegetation dormancy and leaf shedding (Mishra *et al.*, 2021; Nandi *et al.*, 2020) [7, 8].

Spatially, areas dominated by Casuarina equisetifolia plantations and sand dune vegetation showed moderate

NDVI values, reflecting their adaptive resilience to water stress and saline conditions. In contrast, patches of scrub forest and open coastal grasslands displayed low NDVI, signifying sparse vegetation and reduced biomass. These findings are consistent with those of Kumari *et al*. (2023) [5], who emphasized the vulnerability of coastal forests during the dry phase prior to monsoonal recharge. Moreover, the temporal comparison across years revealed slight variations in NDVI intensity, influenced by antecedent rainfall and the residual impacts of cyclonic events such as Amphan (2020) and Yaas (2021), which temporarily altered canopy structure and vegetation density (Mishra *et al*., 2025) [6].

Overall, the Pre-Monsoon NDVI trend underscores the seasonal vegetation stress prevalent in the sanctuary and highlights the dependence of this fragile coastal ecosystem on monsoonal precipitation for regeneration and biomass recovery. The observed fluctuations further illustrate the ecological sensitivity of the Balukhanda-Konark region to climatic variability and hydrological constraints, warranting continuous monitoring for sustainable forest and biodiversity management.

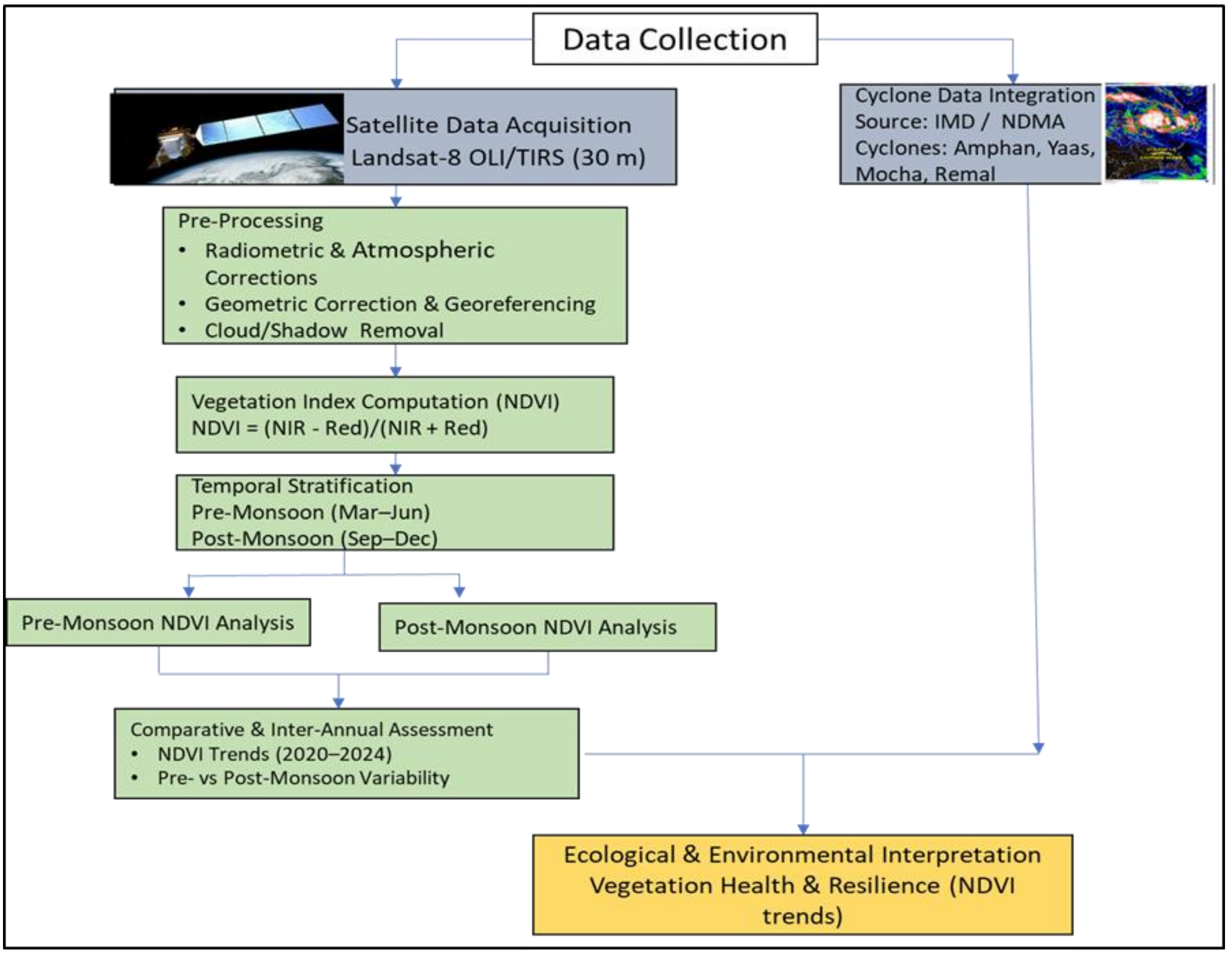

Fig 2: Flow chart of the data collection Method

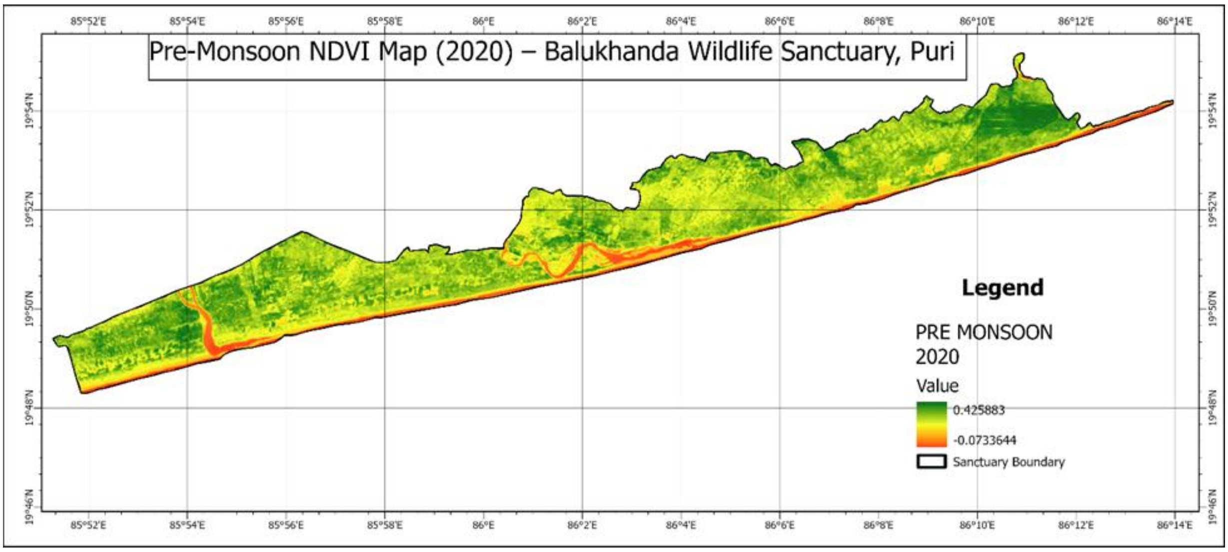

Fig 3: Pre-Monsoon NDVI map (2020) of the study area

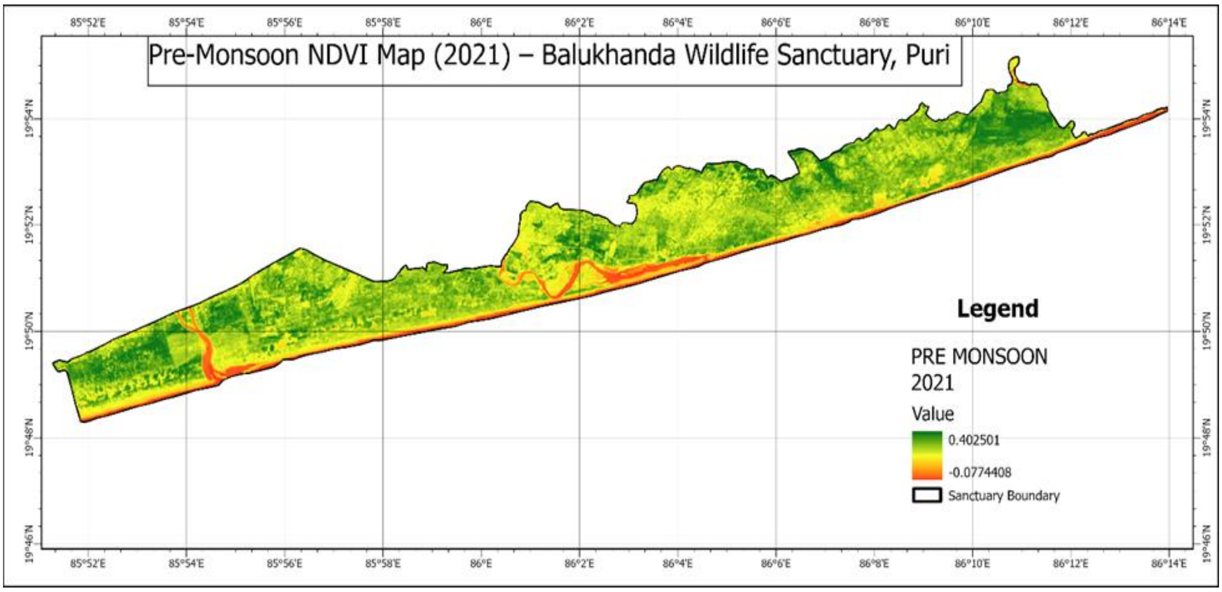

Fig 4: Pre-Monsoon NDVI map (2021) of the study area

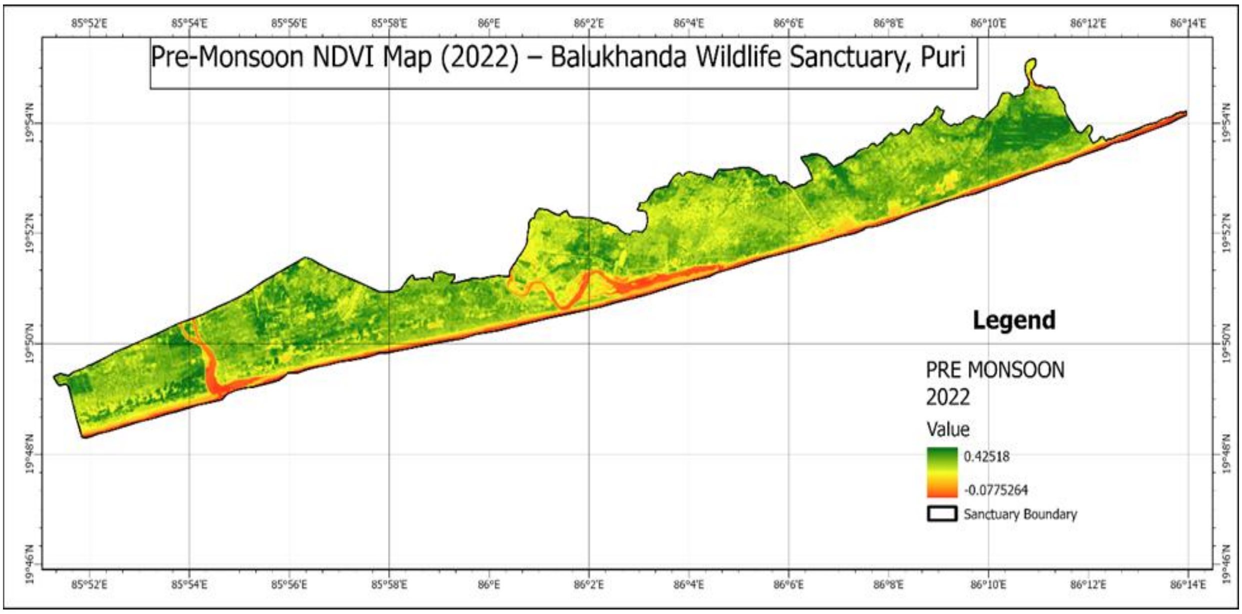

Fig 5: Pre-Monsoon NDVI map (2022) of the study area

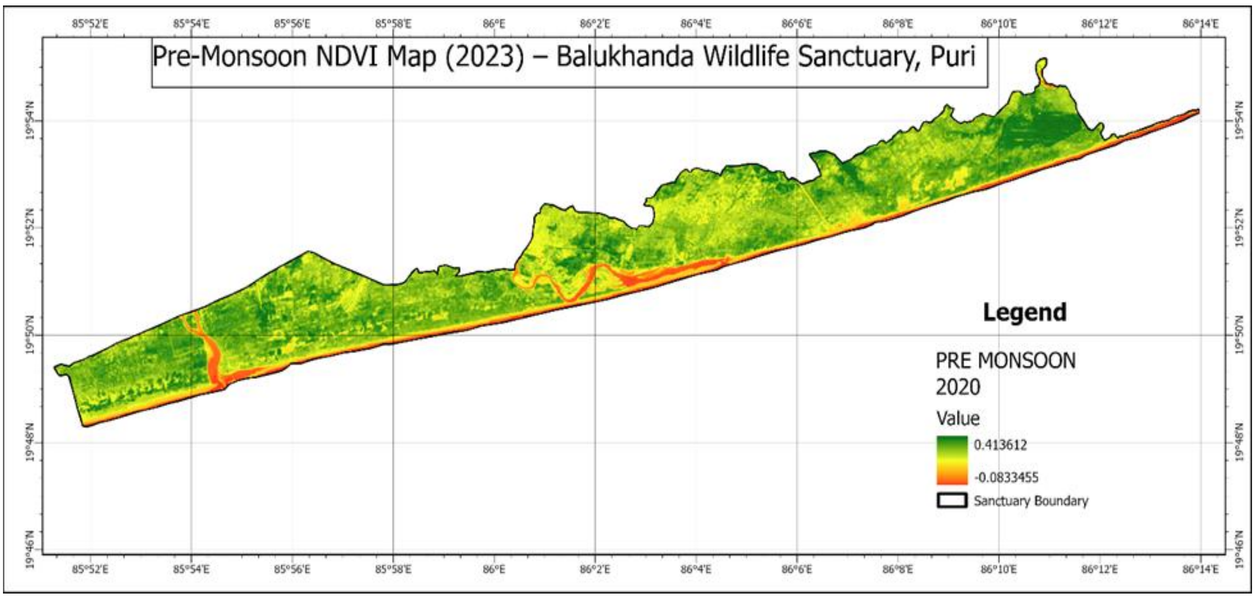

Fig 6: Pre-Monsoon NDVI map (2023) of the study area

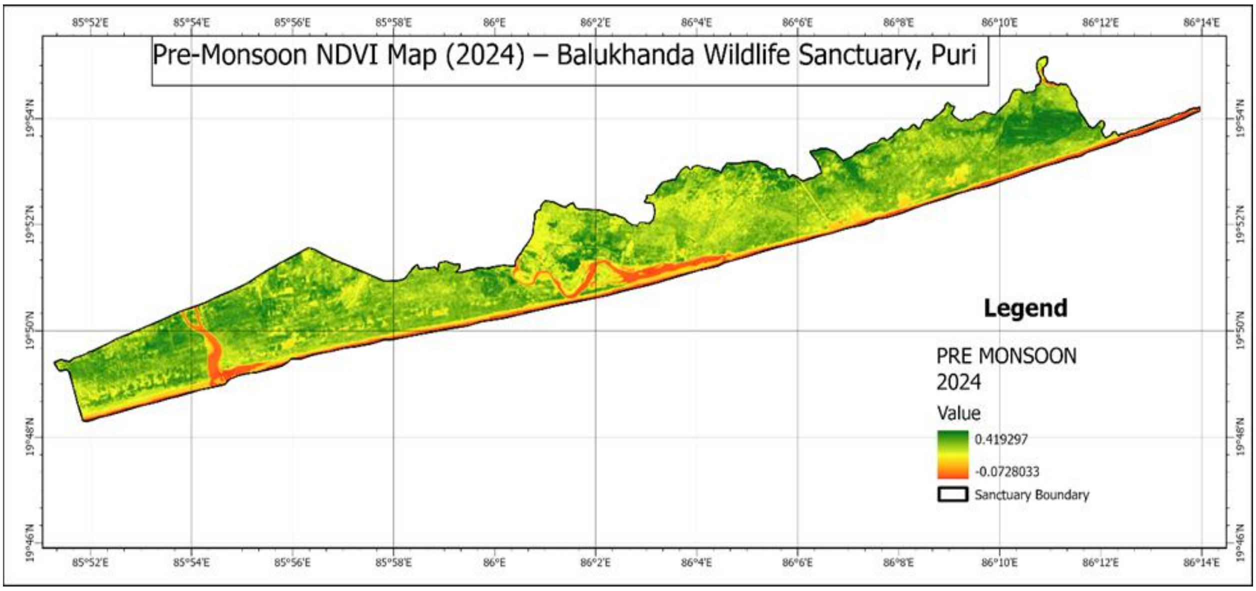

Fig 7: Pre-Monsoon NDVI map (2024) of the study area

3.2 Post-Monsoon Vegetation Status

The Post-Monsoon NDVI map represents vegetation conditions in Balukhanda-Konark Wildlife Sanctuary during the Post-Monsoon season (September-December) for the study period 2020-2024. This season corresponds to the period immediately following the monsoon rains, when vegetation recovery and regrowth are typically observed.

The Post-Monsoon NDVI analysis for 2020-2024 reveals significant vegetation recovery within the Balukhanda-Konark Wildlife Sanctuary (BKWLS) following the annual monsoon rains. During the post-monsoon season (September-December), NDVI values were generally higher compared to the pre-monsoon period, indicating enhanced photosynthetic activity and improved vegetation health. This seasonal increase reflects the replenishment of soil moisture and the favorable climatic conditions that promote regrowth in both natural scrub forests and Casuarina equisetifolia plantations. Spatial patterns showed that areas previously stressed during the dry pre-monsoon season exhibited substantial recovery, whereas some patches affected by cyclonic disturbances such as Amphan (2020) and Yaas (2021) still showed lower NDVI values, highlighting localized lag in vegetation regeneration (Mishra *et al*., 2021; Nandi *et al*., 2020) [7, 8].

The temporal comparison across the study period indicates that the sanctuary's vegetation demonstrates resilience to seasonal climatic variability and episodic cyclonic events. The findings align with earlier studies emphasizing the adaptive capacity of coastal forests to monsoonal cycles and post-disturbance recovery processes (Kumari *et al*., 2023; Mishra *et al.*, 2025) [5, 6]. Overall, the Post-Monsoon NDVI trends underscore the crucial role of monsoonal rainfall in restoring ecosystem productivity and maintaining the ecological stability of this sensitive coastal region.

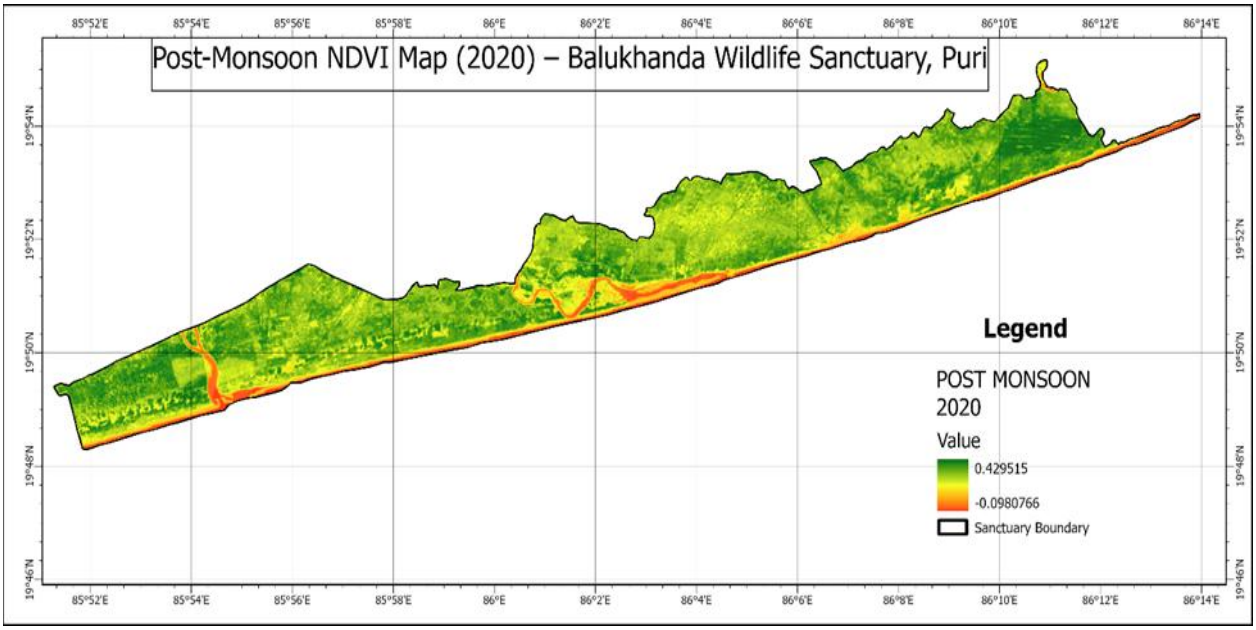

Fig 8: Post-Monsoon NDVI map (2020) of the study area

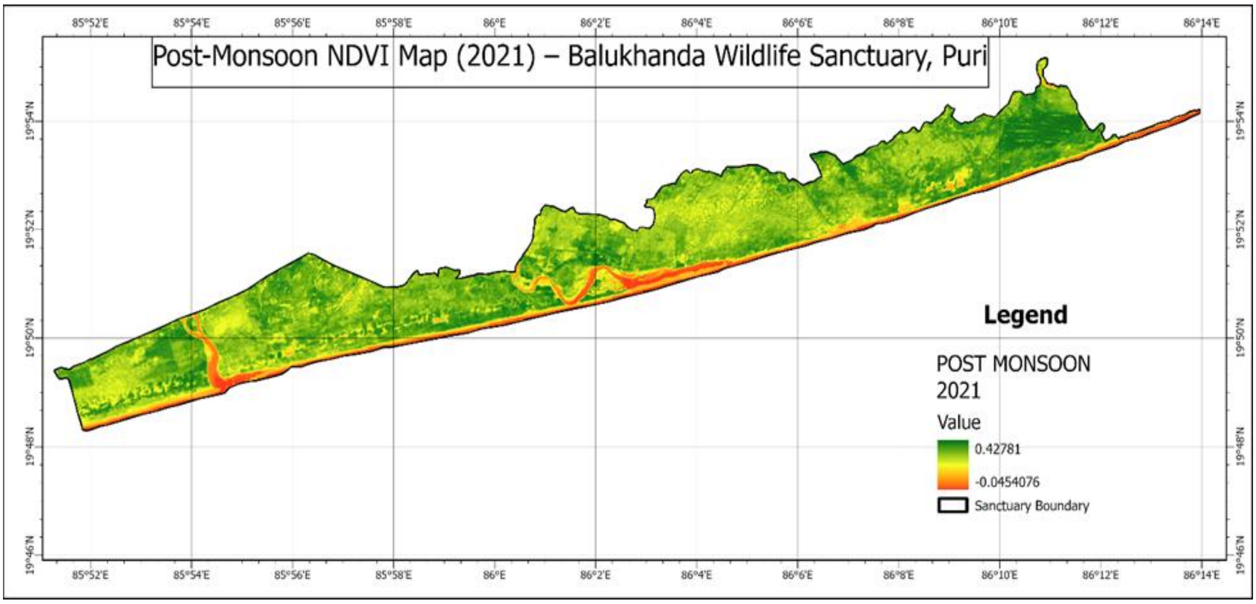

Fig 9: Post-Monsoon NDVI map (2021) of the study area

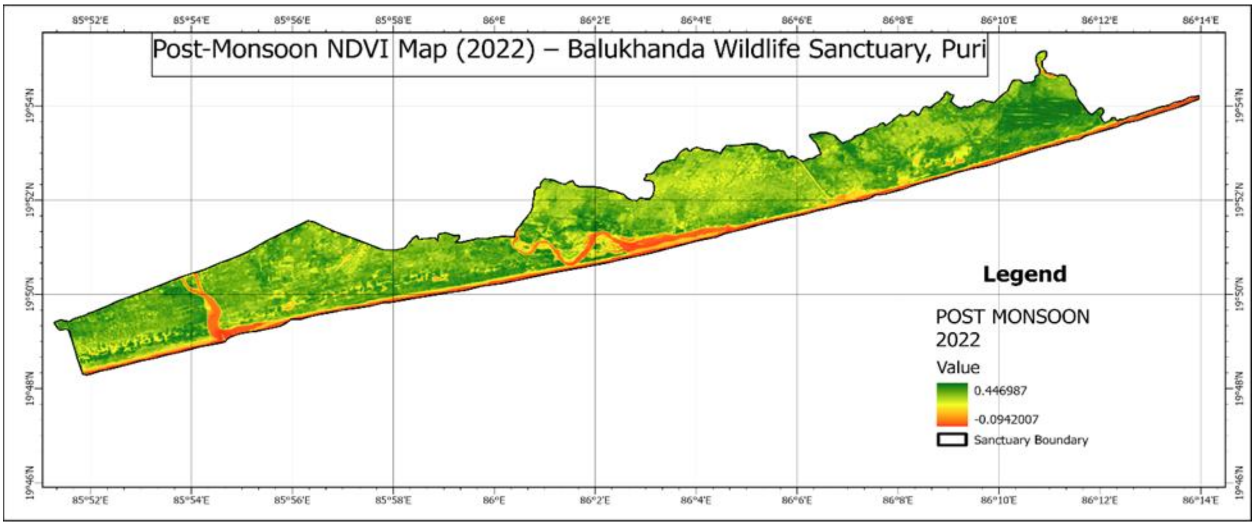

Fig 10: Post-Monsoon NDVI map (2022) of the study area

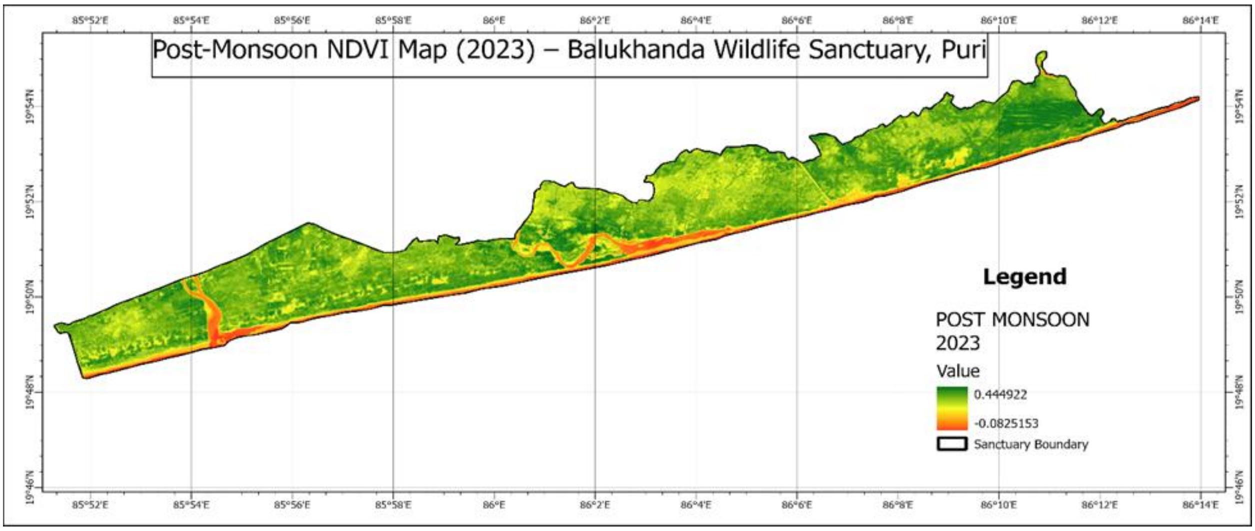

Fig 11: Post-Monsoon NDVI map (2023) of the study area

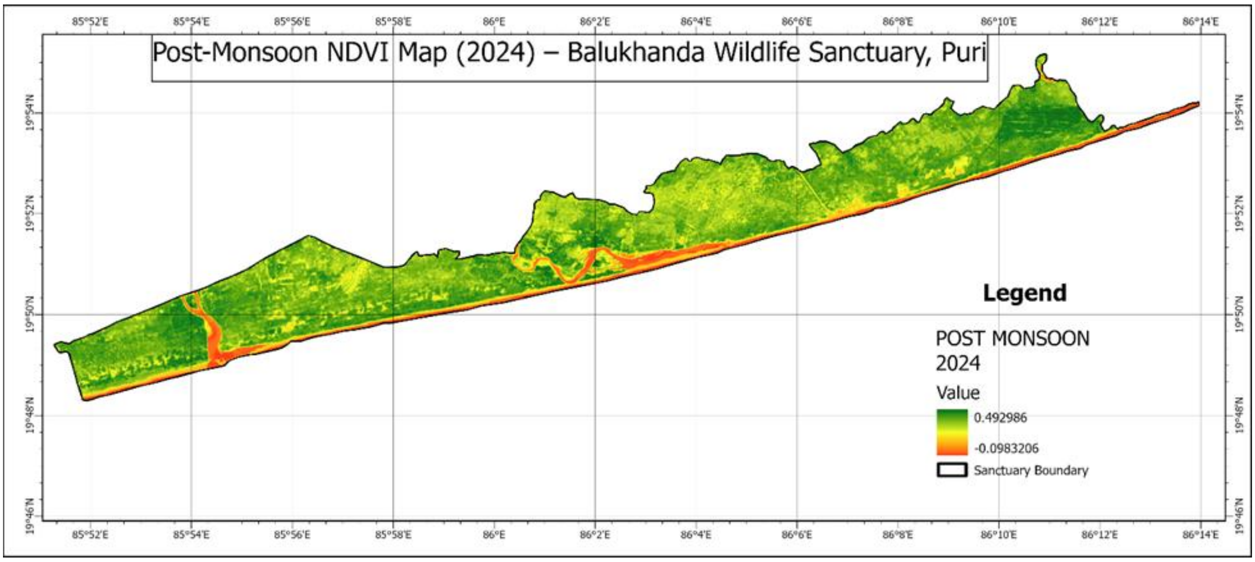

Fig 12: Post-Monsoon NDVI map (2024) of the study area

Table 1: Seasonal NDVI Trend (2020-2024)

Year	Post-Monsoon Max NDVI	Post-Monsoon Min NDVI	Pre-Monsoon Max NDVI	Pre-Monsoon Min NDVI
2020	0.4295	-0.0980	0.4258	-0.0733
2021	0.4278	-0.0454	0.4025	-0.0774
2022	0.4469	-0.0942	0.4251	-0.0775
2023	0.4449	-0.0825	0.4136	-0.0833
2024	0.4929	-0.0983	0.4192	-0.0728

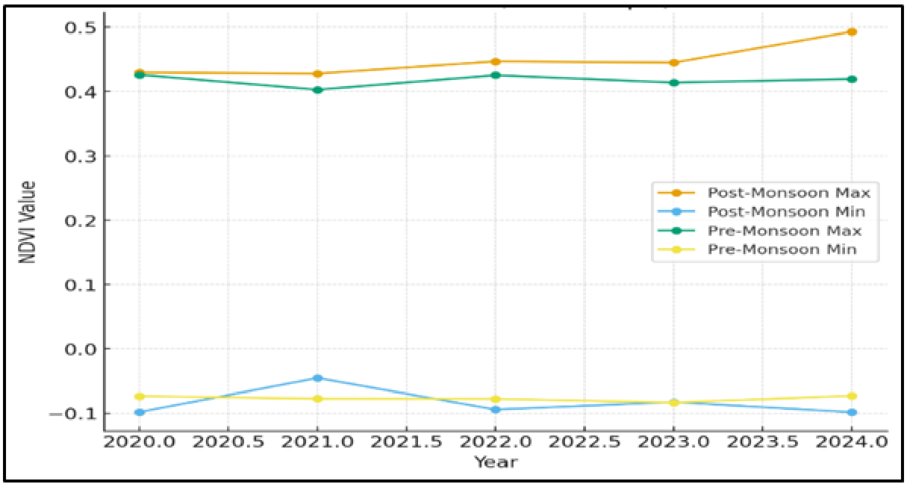

Fig 13: NDVI trends of Pre and Post Monsoon (2020-2024) of the study area

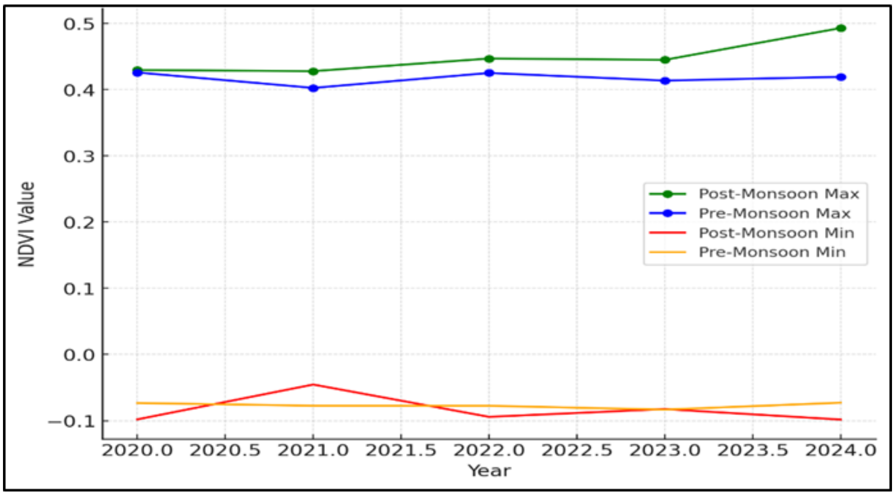

Fig 14: NDVI Extremes of Pre and Post Monsoon (2020-2024) of the study area

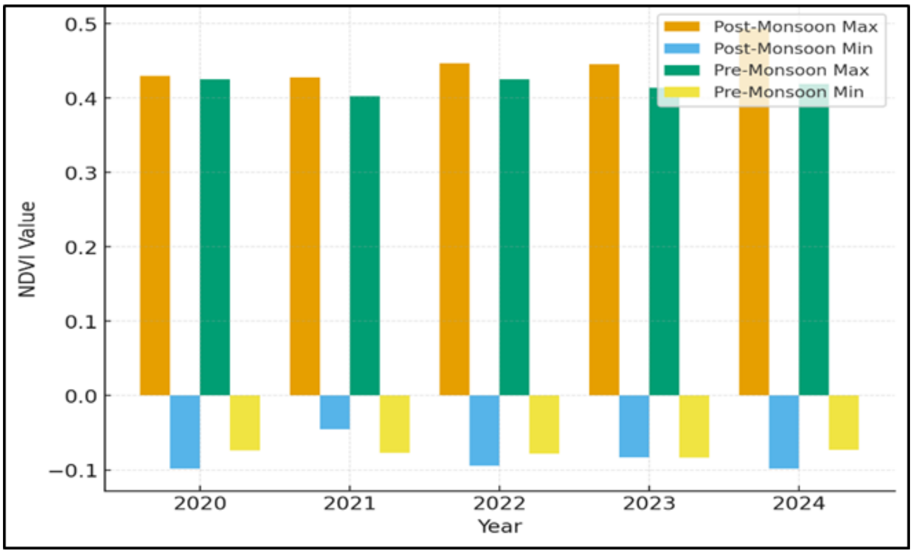

Fig 15: Comparison of NDVI Value of Pre and Post Monsoon (2020-2024) of the study area

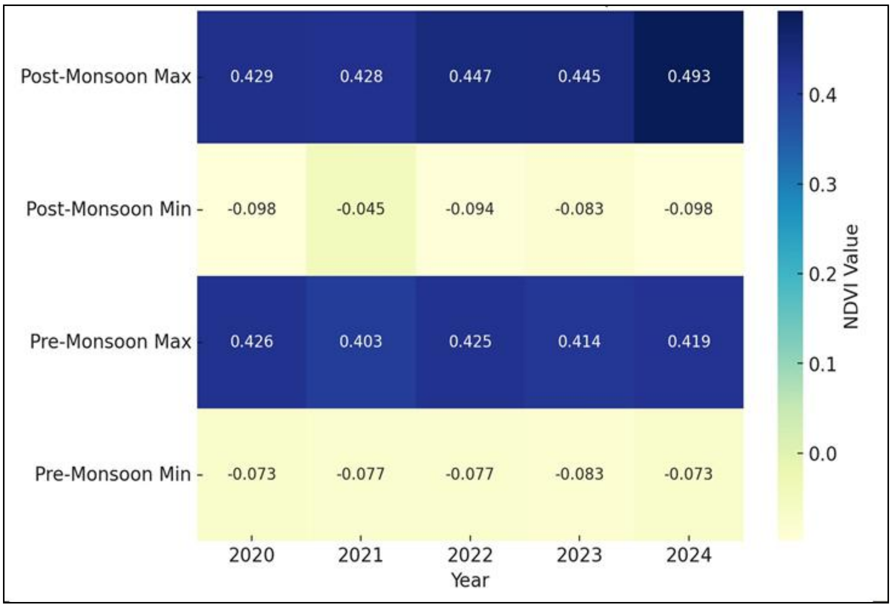

Fig 16: NDVI Variation (Heat map) of Pre and Post Monsoon (2020-2024) of the study area

The Normalized Difference Vegetation Index (NDVI) analysis from 2020 to 2024 reveals a clear pattern of seasonal variation and cyclone-induced vegetation changes along the Odisha coast. Generally, post-monsoon NDVI values are higher than pre-monsoon values, indicating enhanced vegetation growth and greenness following the monsoon rains.

In 2021, the lowest NDVI value (0.4025) was recorded during the pre-monsoon season, which corresponds to the impact of Cyclone Yaas, as the strong winds and heavy rainfall caused significant vegetation stress and damage. Conversely, in 2024, the highest NDVI value (0.4929) was observed during the post-monsoon season, reflecting robust vegetation regeneration and ecosystem recovery after Cyclone Remal.

Overall, the analysis demonstrates that cyclonic events significantly influence vegetation dynamics in coastal Odisha, with NDVI serving as an effective indicator for monitoring post-cyclone recovery and ecosystem resilience.2020 → Super Cyclone Amphan (May 2020).

Severe wind damage uprooted coastal vegetation. NDVI during Pre-Monsoon 2020 slightly depressed (0.4258).

Between 2021 and 2024, the NDVI trends along the Odisha coast reflect the impacts of cyclonic activity and seasonal rainfall on vegetation greenness.

In 2021, Cyclone Yaas made landfall near Balasore in May, bringing strong coastal winds to Puri. This led to sand deposition and saltwater intrusion, which severely stressed vegetation, resulting in the lowest pre-monsoon NDVI of 0.4025 in the dataset.

In 2022, no severe cyclones struck the region, with only minor depression events occurring. As a result, vegetation recovered, and NDVI values improved to 0.4251 pre-monsoon and 0.4469 post-monsoon.

In 2023, Cyclone Mocha in the Bay of Bengal did not make landfall in Odisha, but the associated strong winds and heavy pre-monsoon rainfall caused vegetation stress, reflected in a pre-monsoon NDVI of 0.4136. However, post-monsoon NDVI rebounded to 0.4449, indicating partial recovery.

In 2024, Cyclone Remal affected the region, bringing heavy rainfall that significantly enhanced vegetation growth. This resulted in the highest post-monsoon NDVI of 0.4929, demonstrating strong regeneration after cyclonic impact.

These observations highlight the sensitivity of coastal vegetation to cyclones and rainfall patterns, with NDVI effectively capturing both damage and recovery cycles in the ecosystem.

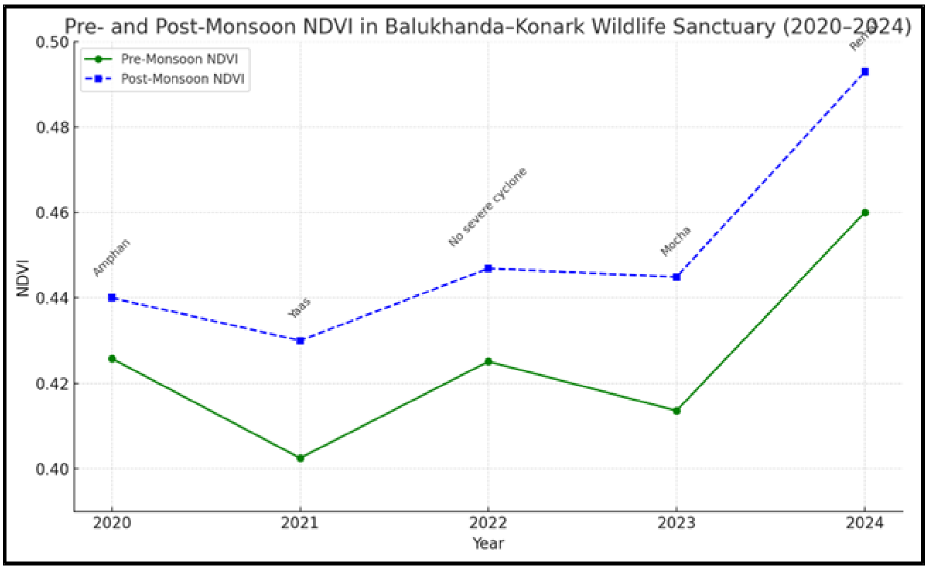

Fig 17: Seasonal NDVI Trends (Pre- and Post-Monsoon, 2020-2024) and cyclone impacts in the study area

3.3 Impact of Cyclones on NDVI and Vegetation Dynamics

Cyclonic disturbances exert pronounced effects on the vegetation structure and health of Balukhanda-Konark Wildlife Sanctuary, which are readily observable through NDVI analysis. Strong winds associated with cyclones often lead to the uprooting of *Casuarina equisetifolia* plantations, which serve as natural cyclone barriers, resulting in reduced canopy cover and lower NDVI values. In addition, saltwater intrusion caused by storm surges can severely damage ground vegetation and root systems, further diminishing photosynthetic activity and NDVI indices. Coastal processes such as sand deposition during cyclones can bury existing vegetation and expand barren areas, which are reflected in negative or very low NDVI signals.

Despite these disturbances, the ecosystem exhibits considerable resilience. Following monsoonal rainfall, damaged vegetation often regenerates, and NDVI values recover during the post-monsoon season, indicating active regrowth and restoration of canopy cover. This cyclical pattern underscores the dynamic interplay between extreme climatic events and ecosystem recovery, highlighting both the vulnerability and adaptive capacity of coastal vegetation in the sanctuary.

3.4 NDVI Pattern Explanation

During the pre-monsoon period (March-June), NDVI values are generally lower, reflecting the combined effects of dry season stress and the impacts of cyclones, particularly in 2020 and 2021, which caused vegetation damage and reduced greenness.

In contrast, during the post-monsoon period (September-December), NDVI values tend to be higher due to the replenishing effects of monsoon rainfall, which promote vegetation growth. This seasonal greening often partially offsets or masks the damage caused by cyclonic events, resulting in improved post-monsoon NDVI levels.

2021 Pre-Monsoon NDVI lowest (0.4025): Cyclone Yaas damage. 2024 Post-Monsoon NDVI highest (0.4929): Strong regrowth after Cyclone Remal.

NDVI fluctuations are governed by both cyclone disturbance + monsoon rainfall patterns.

The study confirms that NDVI is a sensitive indicator of cyclone impacts on coastal vegetation. Cyclones temporarily depress vegetation greenness due to uprooting, salinity intrusion, and sand deposition. However, monsoon rains rejuvenate vegetation, leading to higher Post-Monsoon NDVI.

The casuarina plantations show resilience with rapid regrowth after damage, but negative NDVI zones indicate areas of sand dunes and coastal erosion. Hence, vegetation response is a mix of stress + regeneration cycles driven by climatic extremes.

4. Conclusion

The NDVI analysis highlights the significant influence of cyclones and monsoon rainfall on coastal vegetation dynamics. In 2021, the pre-monsoon NDVI reached its lowest value (0.4025) due to the severe impact of Cyclone Yaas, which caused vegetation damage through uprooting, salinity intrusion, and sand deposition. Conversely, in 2024, the post-monsoon NDVI peaked at 0.4929, reflecting strong vegetation recovery following Cyclone Remal, aided by abundant monsoon rainfall.

Overall, NDVI fluctuations in the study area are controlled by the combined effects of cyclonic disturbances and seasonal rainfall patterns. The analysis confirms that NDVI is a sensitive and reliable indicator of cyclone impacts on vegetation, capturing both damage and subsequent recovery. Casuarina plantations, in particular, demonstrate resilience with rapid regrowth after cyclonic events, whereas areas showing negative NDVI values correspond to sand dunes and zones affected by coastal erosion.

In conclusion, the vegetation response along the Odisha coast reflects a dynamic interplay of stress and regeneration cycles, driven by climatic extremes, highlighting the importance of monitoring NDVI for effective ecosystem management and coastal resilience planning.The NDVI analysis of Balukhanda-Konark Wildlife Sanctuary from 2020 to 2024 demonstrates pronounced seasonal variability and the significant influence of cyclonic disturbances on vegetation dynamics. Lower NDVI values during the pre-monsoon season reflect heightened vegetation stress driven by dry conditions and the direct impacts of cyclones, including canopy loss, saltwater intrusion, and sand deposition. In contrast, post-monsoon NDVI values indicate robust vegetation recovery, supported by monsoonal rainfall and favorable soil moisture conditions. Cyclonic events produced differential effects; for instance, Cyclone Yaas (2021) led to a marked reduction in NDVI, while Cyclone Remal (2024) coincided with substantial post-event vegetation regeneration. These findings underscore the sensitivity of coastal ecosystems to both seasonal climatic fluctuations and extreme weather events. Systematic NDVI monitoring provides a reliable tool for assessing vegetation health, understanding ecosystem resilience, and informing adaptive management strategies aimed at conserving coastal biodiversity and maintaining ecological stability in vulnerable regions.

5. Recommendations

- Strengthen casuarina and native dune vegetation to mitigate cyclone wind/salt impacts.
- Continuous remote sensing-based NDVI monitoring for detecting ecosystem stress.
- Combine NDVI with ground biodiversity surveys for habitat management.
- Develop early-warning ecological resilience strategies for cyclone-prone zones.

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