Examining the effects of economic zone construction on mangrove forest using Before-After-Control-Impact (BACI)

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Abstract

Mangrove forests along land-sea interface are threatened, although they provide diverse ecosystem services. Mangrove transplantation has been conducted in Bangladesh since 1966 to protect coastal areas, although an economic zone project started in 2016 has affected the forest. To evaluate the impact of the project on the mangrove, changes in normalized difference vegetation index (NDVI) were monitored before (2011) and after (2021) the economic zone construction by IKONOS (0.8 m in resolution) and TripleSat (0.8 m) imageries. Before-after-control-impact (BACI) assessment was applied to investigate the effects on the ecosystems with forests surveyed in 18 plots of which disturbance intensities were scored by hierarchical disturbance rank. NDVI decreased in 17.4% of the study area, primarily due to road construction and forest degradation near the economic zone. In all affected plots, NDVI was lower in the after-period than in the before-period. Inland areas showed a positive relationship with NDVI in the after-period compared to seaside. The impact extended up to approximately 20 km beyond the zone, indicating that the effects of construction were extensive. Periods and disturbance intensities were negatively correlated with NDVI changes. In this study, BACI assessment was applied to remote sensing for the first time and identified that low NDVI occurred in the intermediate area, confirming the negative impact of road construction on mangrove for long distance from the project. Considering that human activity leads to mangrove deterioration in both proximal and remote areas, a BACI-based assessment should be adopted when evaluating impacts on mangroves even at remote sensing.

Keywords Mangrove · Economic zone construction · Satellite imageries · Normalized difference vegetation index (NDVI) · Before-After-Control-Impact (BACI)

Introduction

Mangrove forests are found along tropical and subtropical coastlines, particularly in intertidal zones along estuaries, riverbanks and lagoons (Wang et al., 2019). Serving as interfaces between land and sea, they act as coastal buffers mitigating the impacts of disasters (De Alban et al., 2020). Mangroves are more efficient at carbon sequestration than other forest types (Blankespoor et al., 2016). Moreover, mangrove forests play a crucial role in sustaining the health of coastal ecosystems worldwide (Hu et al., 2020).

Mangrove forests are facing threats across their range (Thomas et al., 2017) and have been deteriorating due to land use conversion (Rhyma et al., 2020). Because land use conversion results in permanent destruction of the ecosystems (Zhu et al., 2021). The destruction of mangroves reduces the stability of ecosystems and releases carbon (Hamilton and Friess, 2018). When mangrove cover and health are decreased, human communities become more susceptible to natural disasters and lose vital resources provided by the forest (Mukul et al., 2020). Therefore, any development near mangroves should consider mangrove health to safeguard the delicate ecology of mangroves.

Bangladesh is recognized for hosting one of the most extensive mangrove transplantation projects globally (Chowdhury et al., 2022). The plantations were conducted mostly by the Bangladesh Forest Department since 1966 (Iftekhar and Islam, 2004). Transplanted mangrove areas in Bangladesh decreased by 9.4% from 1996 to 2016 (Uddin et al., 2022). The likely causes of mangrove plantation loss in Bangladesh include excessive use of mangrove resources by coastal people, conversion to shrimp farming, agrarian production, unplanned industrialization, such as the growth of shipbreaking industries, development of industrial zone and salt cultivation (Ullah et al., 2010). Plantation mangrove loss rate in Bangladesh exceeded the annual loss of mangrove cover worldwide (Uddin et al., 2022). In 1976, an afforestation initiative began in the Mirsharai region, southeastern Bangladesh, to enhance coastal protection (Uddin et al., 2014), which was bare land (Saenger and Siddiqi, 1993). In 2014, Bangladesh Economic Zone Authority selected an area near to the Mirsharai mangrove afforestation for special economic zone development, based on its location, proximity to the highway and land availability (BEZA, 2014). The special economic zone represents the first government-driven economic zone in Bangladesh to feature infrastructure and services aligned with international standards (UNCTAD, 2020). Since 2000, economic zones have expanded across developing nations, serving as catalysts for foreign direct investment, industrialization and employment generation (Ortega et al., 2015; Aiyer, 2017). However, the effects of economic zone on natural ecosystems, represented by mangroves, have not been clarified well.

On the study site in southeastern Bangladesh, the economic zone project includes the construction of offsite facilities, such as buildings, roads and sluice gates. Since 2016, ongoing construction activities in and around the economic zone adjacent to the mangrove plantation have posed threats to the area. The sustainable growth of coastal vegetation is impacted by the elimination of mangrove wetlands (Montefalcone, 2009). Therefore, assessing the effects of construction on mangrove forests is required to preserve coastal ecosystems. Although mangrove distribution, biomass and factors of mangrove disturbance have been highlighted at global (Giri et al., 2015) and local scale (Jia et al., 2023), only a few studies have examined mangrove health in response to human activities, such as dredging (Arshad et al., 2020), shrimp farming (Alatorre et al., 2016) and economic zone construction (Ashournejad et al., 2019). These studies primarily analyzed temporal normalized difference vegetation index (NDVI) trends but did not specifically compare impacted and non-impacted areas. In addition, research on mangrove health in relation to economic zone development remains scarce (Aung et al., 2022) and therefore, an attempt has been made in this study to assess mangrove NDVI changes by comparing both at the temporal and spatial scales. Although monitoring mangrove forests, including ground-based surveys, have been conducted well, large-scaled long-term monitoring is required to clarify the ecosystem dynamics at regional scale (Akhtar and Tsuyuzaki, 2024).

In particular, the effects of economic zone developments on mangroves should be investigated at large scale, such as using remote sensing (RS) (Aung et al., 2022). RS monitors changes in mangrove ecosystems (Sunkur et al., 2024) because this is economical, time-efficient and accessible to remote locations (Kuenzer et al., 2011). The health of the mangrove ecosystem is estimated often by vegetation indices (VI) and landscape metrics (Wang et al., 2019) with classification algorithm (Vidhya et al., 2014). VI is obtained from the spectral reflectance of two or more wavebands and is often employed to show the extent and strength of vegetation and corresponds to ground-surface biophysical parameters (Rhyma et al., 2020). NDVI is used to assess vegetation characteristics, including the greenness over time (Tran et al., 2024; Alatorre et al., 2016). NDVI calculated by the reflectance of Red and NIR (near-infrared) has spectral properties for identifying stressed vegetation, particularly sensitive to chlorophyll content in plants by Red band (Adamu et al., 2018).

To monitor the effects of economic zone construction on ecosystems, before-after-control-impact (BACI) assessment was applied, because BACI assessment systematically extracts the effects of impacts and reduces the uncertainty of prediction (Chevalier et al., 2019). BACI measures ecosystem changes spatiotemporally related to the presence and absence of impacts (Hewitt et al., 2001). In BACI assessment, undisturbed control areas are compared with disturbed impacted areas (Stewart-Oaten and Bence, 2001). The effectiveness of BACI using NDVI for assessing mangrove forest change has not been examined at remote sensing scale. If this study confirms the effectiveness of BACI using RS, these methods should be utilized broadly due to the availability of enormous satellite data suitable for BACI.

To ensure the applicability of BACI to NDVI, NDVI fluctuations were investigated by satellite data in the southeastern part of Bangladesh, where the special economic zone was established near the transplanted mangrove. One of the aims of this study is to assess the effects of economic zone construction activities on mangrove forest by NDVI changes based on BACI. The hypothesis is that construction impacts mangrove structure, potentially affecting distant forest areas. This study has two objectives: a) to determine the changes in mangrove forest using NDVI data before and after the construction; b) to evaluate these changes using BACI.

Materials and methods

Study site

The research is conducted in the Mirsharai-Sitakunda coastal forest area of Bangladesh (22°36′ to 22°48′ N and 91°24′ to 91°38′ E) adjacent to the Mirsharai economic zone, facing to southwest towards the Bay of Bengal (Fig. 1). The elevation ranges from 3 to 8 m AMSL. The annual rainfall is 2500-3000 mm (Brammer, 2013). The maximum monthly temperature reaches 33.4°C, while the minimum is 14.1°C. During monsoon season (June to October), relative humidity averages 80% at a weather station 4.5 km far from the study site. Approximately 80% of annual rainfall occurs between May to October (BMD, 2023). Soil salinity near the coast ranges from 4 to 26 dS/m (SRDI, 2010).

Bangladesh Government has led the afforestation of mangroves since the early 1970s in the study area (Uddin et al., 2022). Bangladesh was one of the pioneer countries in South Asia to widely establish mangroves on accreted coastline, formed from river sediments (Siddiqi and Khan, 2004). *Porteresia coarctata* (Roxb.) Tateoka (Poaceae) colonizes the newly formed land within a few years after the sediment bank development when the sediments attain around sea level (Uddin et al., 2022). The objectives of the Bangladesh Forest Department (BFD) are to stabilize newly accreted coastal lands, mitigate damage from severe climatic events and boost resilience through adaptation to the climate change impacts (BFD, 2018). Once *P. coarctata* is established, the BFD counts the land fit for planting pioneer mangrove species, e.g., *Sonneratia apetala* Banks and *Avicennia officinalis* L. (Saenger and Siddiqi, 1993). The initial seedling density was generally 4444 /ha (Siddiqi, 2001).

In the study site, Mirsharai-Sitakunda forest ranges, common planted species are *S. apetala, Excoecaria agallocha* L., *A. officinalis, Ceriops decandra* (Griff.) Ding Hou and *Bruguiera sexangula* (Lour.) Poir. (Haque et al., 2000). The tree density was 285/ha. During 2019 to 2020, the forest height varied from 0 to 13 m depending on the transplantation ages, and aboveground biomass averaged 62 ± 6 Mg ha^{-1} in the study site (Uddin et al., 2022).

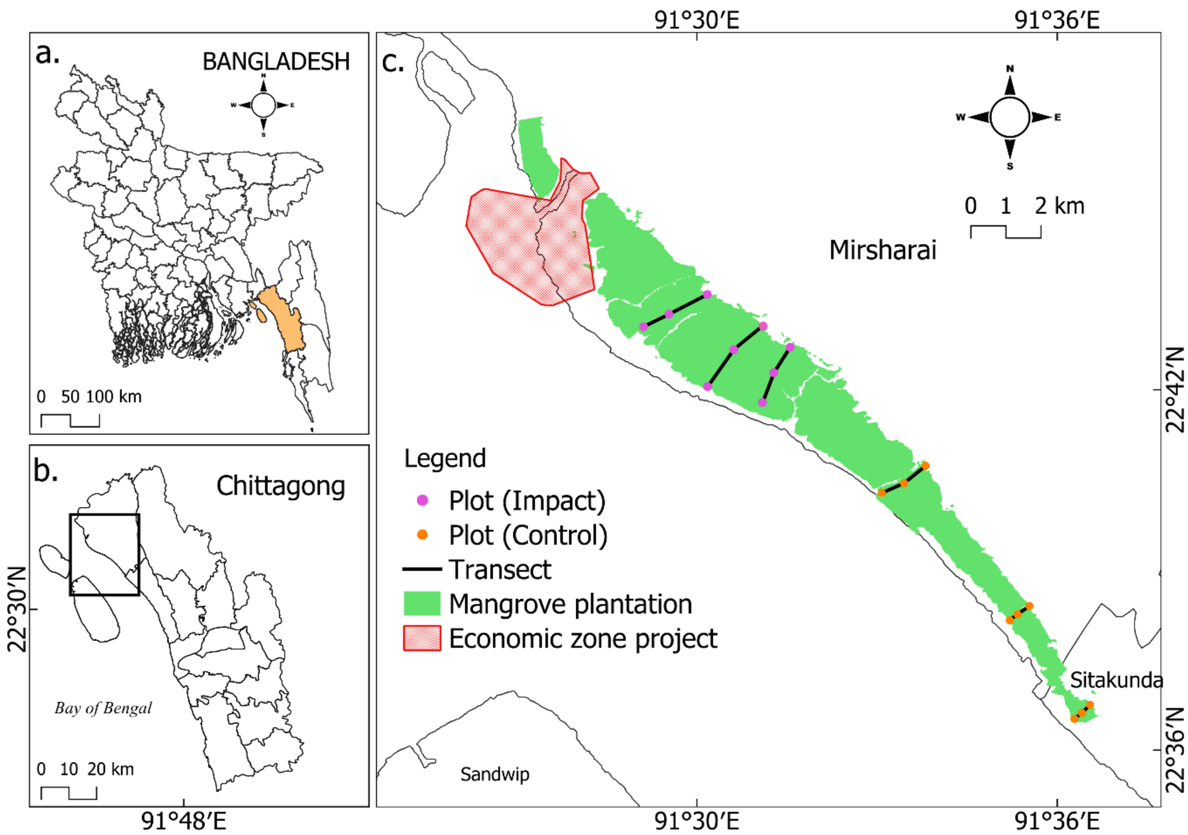

Fig. 1 Study area (a) Location of Chittagong, shown in orange, in the southeastern coast of Bangladesh (b) Location of the study area in Chittagong, shown by the bolded section (c) Study area characteristics. The mangrove plantation area is shown in green, while the economic zone is indicated in red. Within the mangrove area, six belt transects, delineated by thick black lines, are established for vegetation surveys. Each transect contains three 10 m × 10 m plots. Based on their location within the surveyed mangrove forests, plots were categorized as seaside, intermediate and inland. According to disturbance rank score, nine plots situated closer to the

economic zone are classified as impacted plots, shown in purple, while the remaining plots, shown in orange, located far from the zone, serve as controls

The mangrove forests developed zonally along the seacoast (Fig. 1). Since mangrove forests located closer to the sea are more influenced by marine factors (Uddin et al., 2014), three zones, seaside, intermediate, and inland, were classified based on plot locations in the mangrove forests. Seaside plots were established at the forest edges near the coastline, while inland plots were positioned at the forest edge on the landward side. Intermediate plots were placed at the center of the mangrove zone.

Study design

NDVI was analyzed at 5-year intervals by a BACI assessment. The temporal changes before and after construction were analyzed to show the impacts, while control and impact areas examined spatial differences. The boundary between before-and after-project periods was set at 2016 when the project began. The boundary was adjusted to distance 0.

Field measurements were conducted in November 2021, by six belt transects established orthogonally to the coastline at 1.6 km to 4.5 km intervals (Fig. 1). On each transect, a 10 m × 10 m plot was established in each of the three zones, inland, intermediate and seaside. In total, 18 plots were recorded with the coordinates by a global positioning system (GPSmap 60CSx, Garmin, Schaffhausen, Switzerland). On each tree with more than 1.3 m in height in each plot, species, height and Diameter at Brest Height (DBH) were recorded. Stem height was measured by a laser rangefinder (TruPulse 200, Laser Technology, Inc. Colorado, USA) and DBH was measured by a tape. In each plot, elevation, number of tree stumps, dominant species and canopy openness were recorded. Canopy openness was assessed by photos taken by an android smartphone camera (model A54 5G OPG02) equipped with a fish-eye lens (ALILUSSO 180° Fisheye Lens, ALILUSSO, China). Photos were taken at the center and four corners in every plot at 1.3 m above the ground surface supported by a tripod after horizontal balance was fixed by a two-axis bubble level. Canopy openness and LAI (leaf area index) were calculated by the photo images using Gap Light Analyzer (version 2.0) (Frazer et al.,1999; Tsuyuzaki et al., 2008). Canopy cover (%) was calculated as: 100 – canopy openness.

Quantification of disturbance intensity

To quantify human impacts, a disturbance rank was assigned to each plot (Lopez and Fennessy 2002; Tsuyuzaki and Zhang, 2020), based on the hierarchically ranked significance of disturbances (Karr and Chu, 1997). The four disturbance types were considered hierarchically as (Fig. 2): The top hierarchy of disturbances was infrastructure development, that was the trigger of the alteration of mangrove forests by the construction of built-up and other facilities. Road construction was situated on the second hierarchy, because the roads were developed incidentally with infrastructural development. Sand filling and tree felling were situated on the third and fourth hierarchies, respectively, depending on the intensities and scales of ecosystem damage. The tree felling was recorded as minimal (fewer than 5 tree stumps), moderate (5-10) and substantial (more than 10).

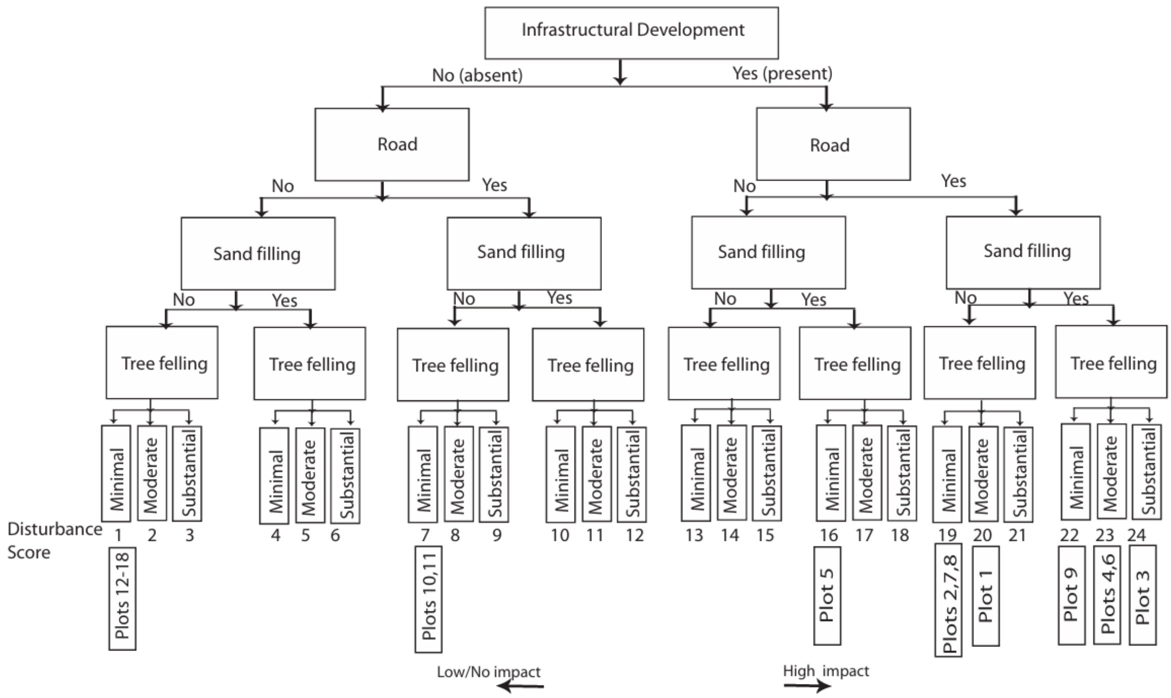

Fig. 2 Hierarchical classification for determining human disturbance score. The activities of infrastructural development, roads, sand filling, and tree felling are considered as major human disturbances. Each numeral shows the disturbance score

Spatiotemporal changes in NDVI using BACI

NDVI was measured in 2011 prior to the construction of the economic zone and in 2021 posterior to the construction based on BACI design. IKONOS images were obtained at 04:35

(GMT) on 10 January 2011, five years before starting the project from Digital Globe-Apollo Mapping, Longmont, Colorado, USA. TripleSat images were acquired at 04:35 on 04 February 2021 at five years after the project from Twenty First Century Aerospace Technology Co. Ltd., Singapore, instead of IKONOS images because of the termination of IKONOS. The cloud cover was 0 on both images. The resolution of the sensors on the two satellites is 0.8 m.

The image processing was performed on JavaScript code editor by the Google earth engine (GEE) (Gorelick et al., 2017). The images were preprocessed by dark object subtraction for atmospheric correction (Huguenin et al., 1997) and were visualized by adjusted parameters in GEE. Two wavelength bands to calculate NDVI were: red (632–698 nm on IKONOS and 600–670 nm on TripleSat) and NIR (757–853 nm and 760–910 nm). The equation of NDVI is (Rouse et al., 1974):

$$NDVI = (NIR - red) / (NIR + red),$$

where reflectance of spectrum components is denoted as red and NIR (Catorci et al., 2021). Change in NDVI difference is:

$$NDVI\ difference = NDVI_{after} - NDVI_{before},$$

where $NDVI_{before}$ and $NDVI_{after}$ are NDVI before and after construction, i.e., 2011 and 2021, respectively. A NDVI threshold was applied to see the changes (Pu et al., 2008). The mean ± one standard deviation of the NDVI differencing image was extracted by the threshold (Dutta et al., 2015). This threshold is used to divide the area into three categories, positive as gain, negative as loss and stable as less change at each pixel (Malow et al., 2018).

To apply BACI to NDVI fluctuations, mean and standard deviation (SD) of NDVI were calculated on each plot using 100 pixels obtained from satellite images because mean NDVI often indicates mangrove greenness (Ruan et al., 2022) and SD increases with the spatiotemporal variations of greenness. Generalized linear model (GLM) was used to investigate the effects of economic zone construction on NDVI. NDVI was a response variable and period (before and after) and disturbance score were the explanatory variables with the assumption of Gaussian error distribution. R was used for statistical analysis (version 4.1.2, R Core Team, 2022).

Results

Overview of forest structure at surveyed plots

E. agallocha is the dominant mangrove species observed in the surveyed plots. Four types of species named *E. agallocha, A. officinalis, S. apetala, C. decandra* (Griff.) along with a few understories, such as *Acanthus ilicifolius* L. and *Tamarix indica* Willd., were recorded. The tree height ranged from 3.8 m to 13.7 m and DBH ranged from 4.6 cm to 29.8 cm in the plots. The number of trees per plot varied from 8 to 333. Canopy coverage ranged between 69.1 ± 4.91% and 20.4 ± 17.4% (Table S.1).

Changes in mangrove forest

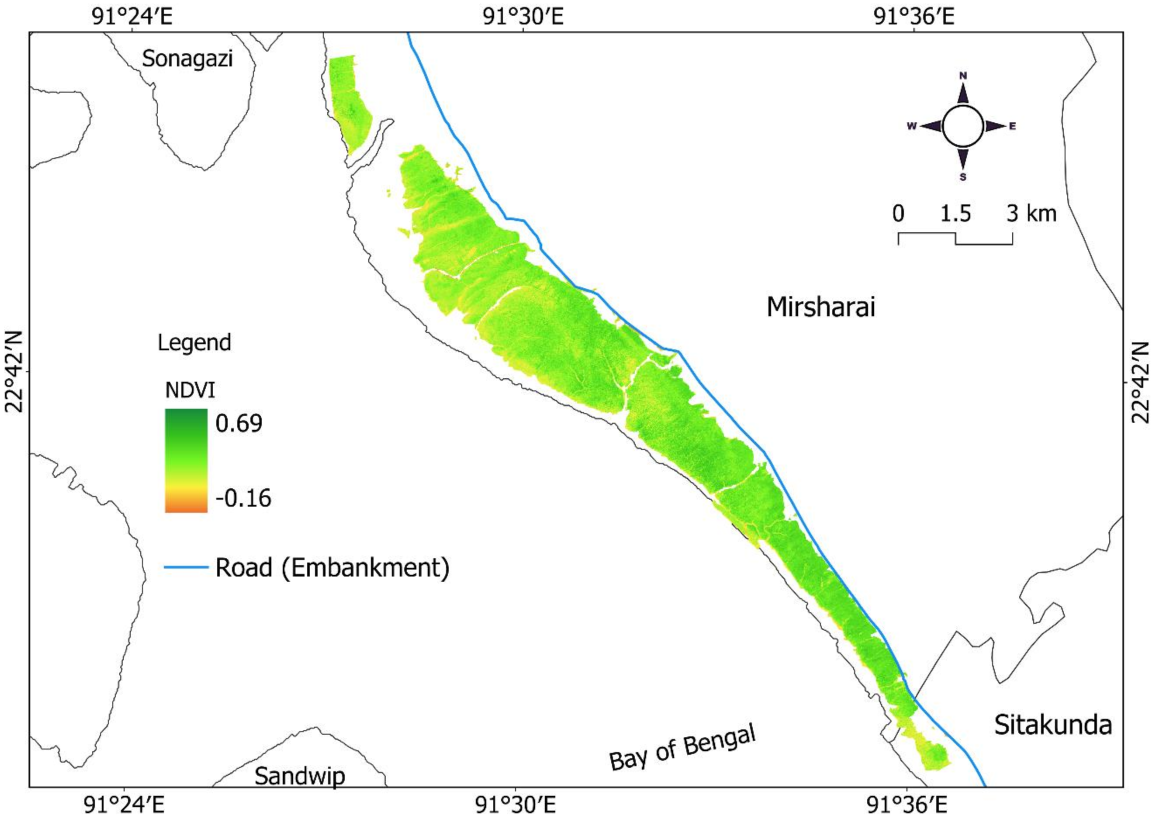

Fig. 3 NDVI distribution in 2011 before the construction of the economic zone

In 2011 before the economic zone construction, there was one embankment road in the eastern side of the mangrove forests (Fig. 3). Although a few areas showed a linear trend of lower NDVI, these areas were not bare ground, including roads. The field observations confirmed that these areas were naturally developed creeks. Therefore, before the built-up construction, road networks in the forests were least.

NDVI decreased in most areas of the northern region close to the economic zone after the construction (Fig. 4), showing that the greenness of mangrove forests was declined mostly by the construction. Not only in the northern region but also in the intermediate region, NDVI declined sporadically and increased in a few areas far from the coastal lines.

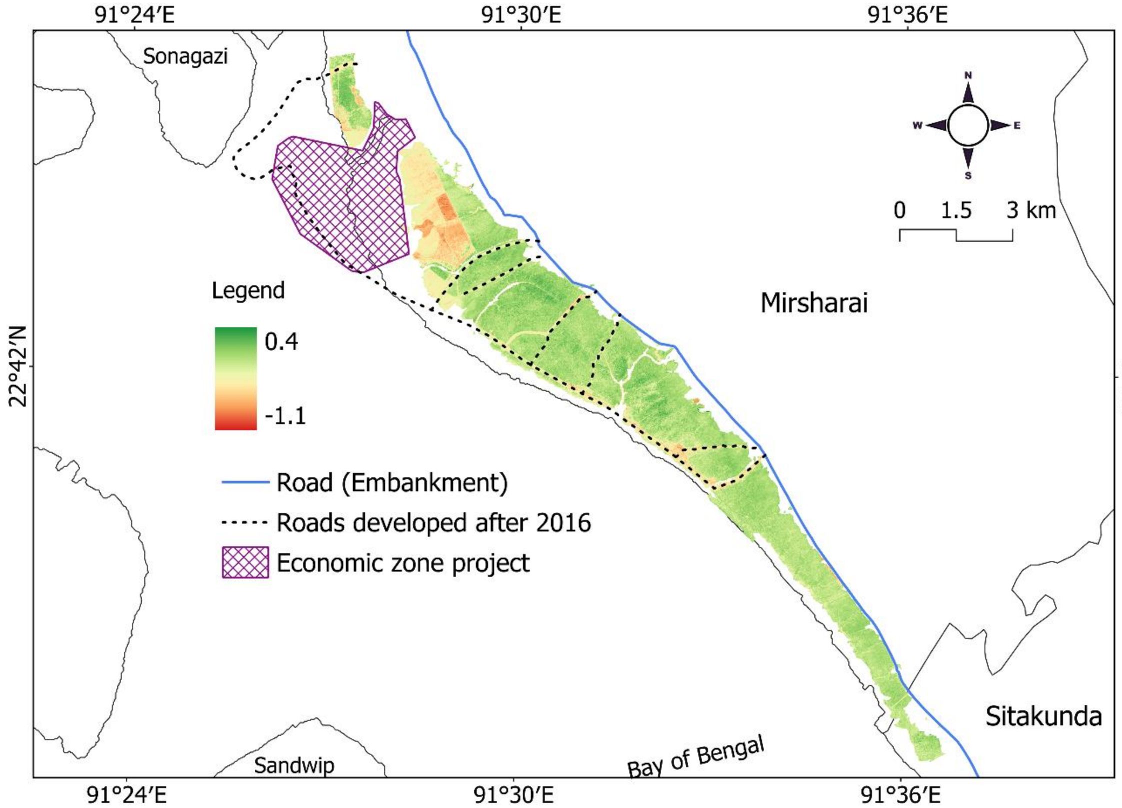

Fig. 4 NDVI differences in the area studied from 2011 to 2021. The road networks developed after the economic zone construction are shown by thick interrupted lines

NDVI in mangroves was stable at 72% (25 km^2) of the area from 2011 to 2021. NDVI decreased 17% of the examined area (6 km^2) and increased 11% (4 km^2). From 2011 to 2021, NDVI decreased largely near the economic zone. Linear shapes of decreasing NDVI areas were observed on the map after the construction (Fig. 5).

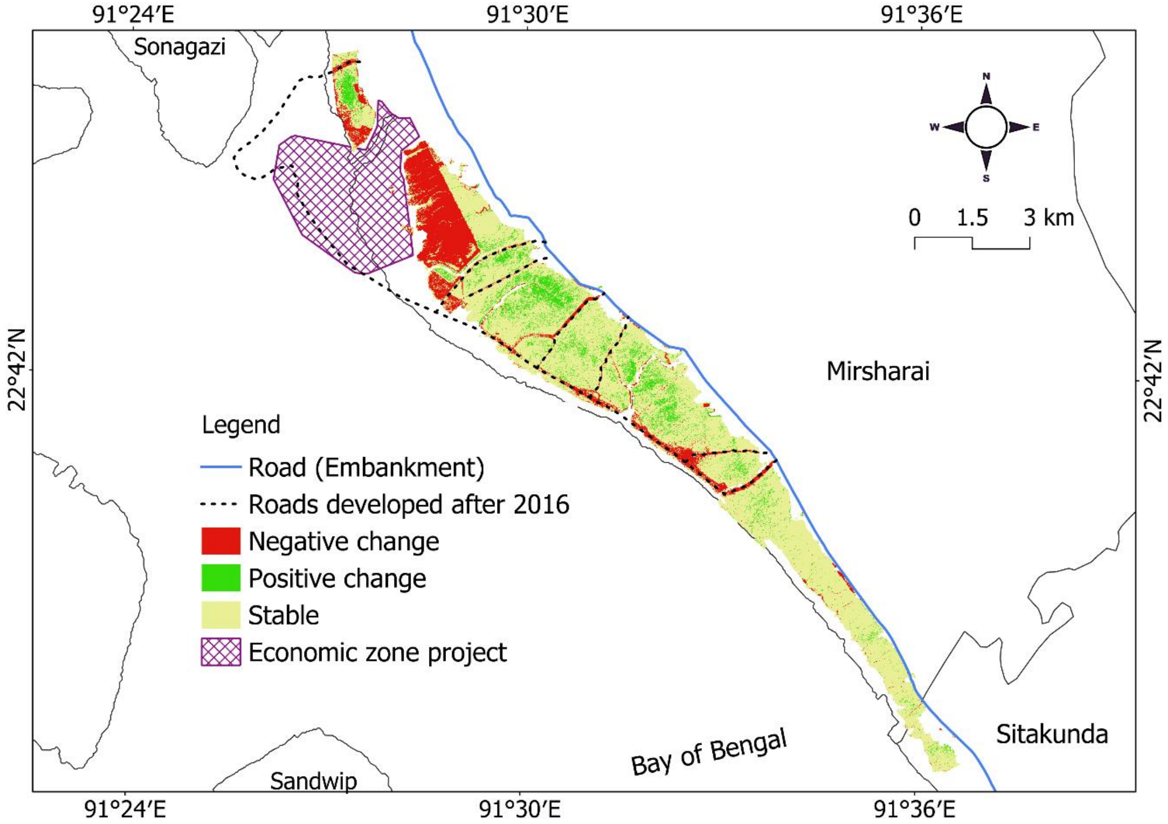

Fig. 5 NDVI change in the mangrove plantation from 2011 to 2021

Determining human disturbance score in impact and control plots

Seven plots were assigned a disturbance score of 1, signifying minimal human impact (Fig. 2). Two plots were assigned to a score of 7, attributed to the impact of sand filling. The remaining nine plots were impacted by the economic zone construction, receiving scores exceeding 16. Therefore, the plots with scores 7 or below were classified as non-impacted controls, while those with higher scores were designated as impacted. All the impacted plots except one were affected by road construction. The number of tree felling varied largely among the plots, i.e., 0 to 23 (Fig. 6). Based on the disturbance scores, 9 plots coded as 1-9 exhibited scores exceeding 16 and were designated as impact. In contrast, the remaining 9 plots (coded as 10–18), each with a score below 7, were designated as control. The criteria of control were basically determined by the effects of infrastructural development and therefore potential bias should be weakened when we focused on the effects of infrastructural development.

a) b)

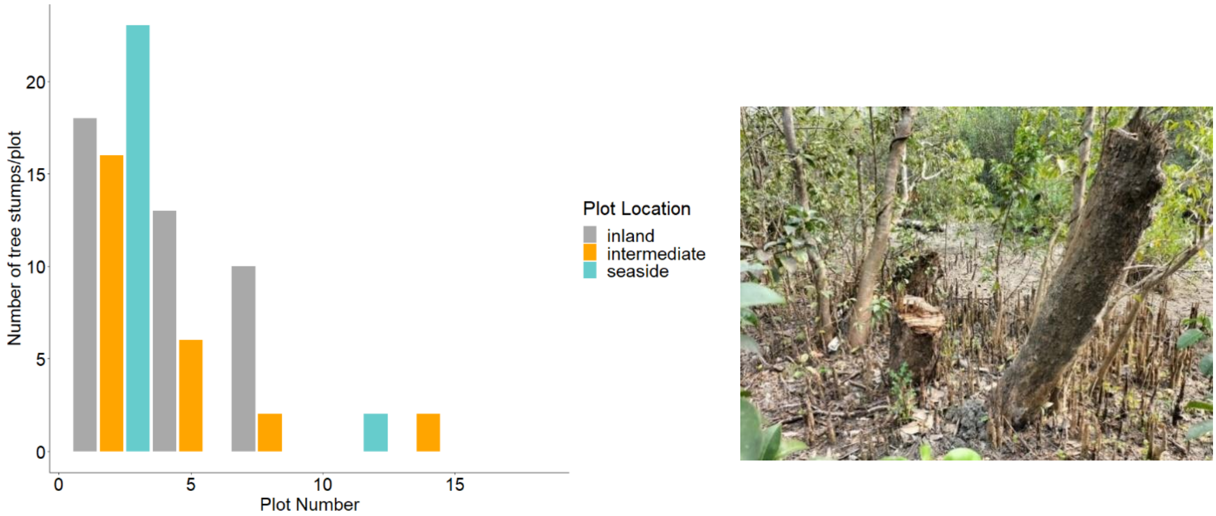

Fig. 6 (a) Number of tree stumps in 18 surveyed plots (b) A tree stump observed in a plot scored 7 in 2021

Table 1 NDVI changes between before and after built-up in each of the three zones (inland, intermediate and seaside). Each numeral indicates mean with standard deviation

Plot location	Plot category	Before (2011)	After (2021)
Inland	Impact	0.244 ± 0.030	0.176 ± 0.039
	Control	0.287 ± 0.055	0.302 ± 0.054
Intermediate	Impact	0.261 ± 0.042	0.186 ± 0.054
	Control	0.308 ± 0.027	0.226 ± 0.031
Seaside	Impact	0.293 ± 0.029	0.191 ± 0.054
	Control	0.282 ± 0.043	0.240 ± 0.051

BACI assessment showed that both the impact and control areas were affected by human activities, although the disturbance intensities were different between them (Table 1). The impacted plots showed lowered NDVI after the economic zone construction in 2021 (GLM, $p < 0.001$). While two inland control plots showed higher NDVI after the construction, two intermediate and seaside plots showed lower NDVI. The inland plots received less human impact than the intermediate and seaside plots. The impact plots showed large fluctuations in the NDVI, as shown by high SD. Decline in NDVI far from the economic zone indicated that human impact extended up to approximately 20 km from the construction (Fig. 7).

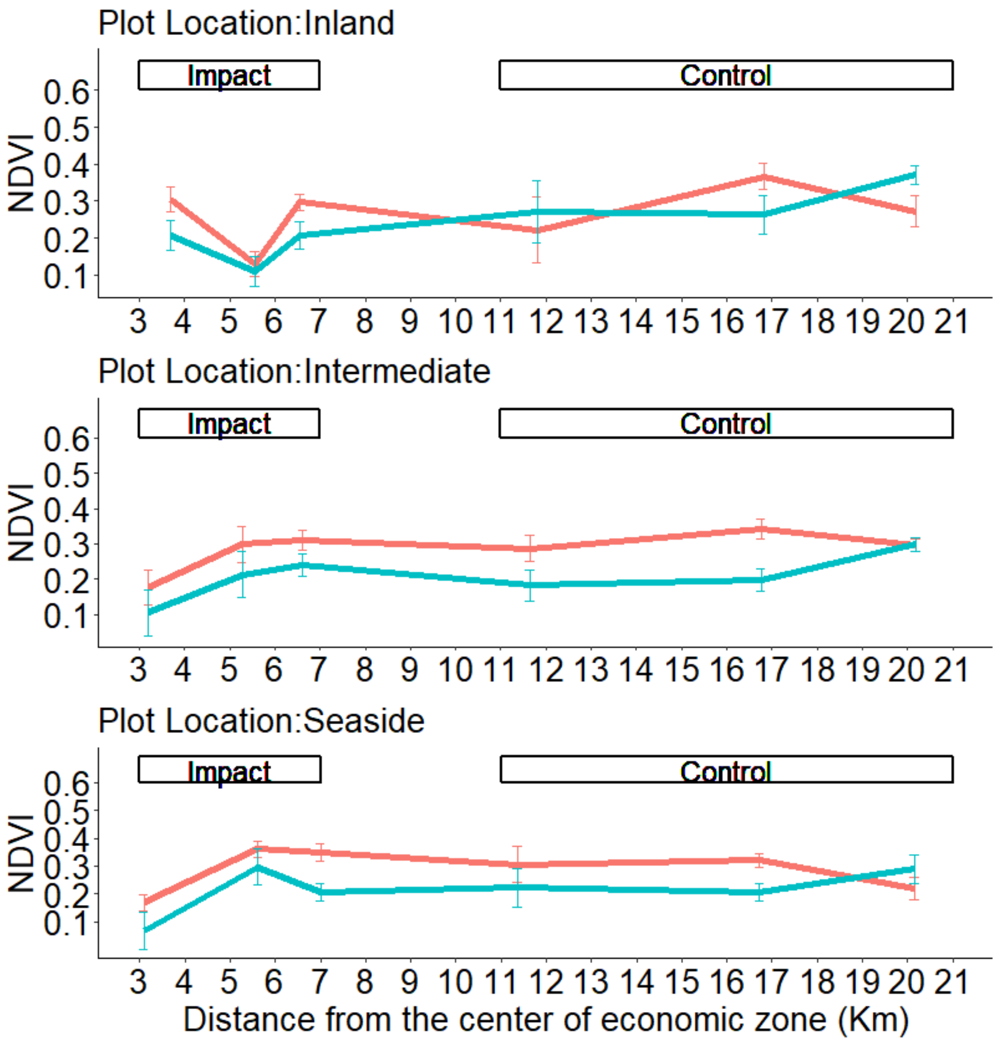

Fig. 7 Changes in NDVI in 2011 (red lines) and 2021 (blue lines) along 18 plots established in relation to distance from the economic zone. The years 2011 and 2021 are before and after the economic zone construction, respectively. Mean is shown with SD (vertical lines)

This study explored the impact of disturbance scores and temporal variations on mangrove health using NDVI between 2011 and 2021. The examine periods and disturbance scores were negatively correlated with NDVI changes (GLM, $p < 0.001$). High disturbance rank score was associated with low NDVI. NDVI decreased in 2021 due to disturbances compared to 2011 ($p < 0.001$).

Discussion

BACI assessment was applicable to investigate the human impacts, i.e., economic zone construction, on mangrove vegetation at the remote sensing scale. NDVI lowered greatly after the impact, mostly in the northern parts of the study area, showing that direct human impacts occurred close to the economic zone. Significant roads were not present in the forest in 2011. In 2021, NDVI decreased far from the construction and occurred with strip-like patterns after the construction, suggesting that the human impact affected long distance when roads were constructed. Overall, the observed decline in NDVI from 2011 to 2021 indicated a deterioration in mangrove health. NDVI indicates vegetation greenness and health, because the degradation of ecosystem vegetation or a decrease in green should be reflected in a decrease in NDVI (Meneses Tovar, 2011).

The BACI approach was initially introduced by Green (1979) and has been increasingly applied to various environmental assessments, with continuous improvements in protocols enhancing its effectiveness (Smokorowski and Randall, 2017; Christie et al., 2020). The collapse of mangrove forests is detected around a mega-construction of industries in the southern coast of Vietnam by RS but the impacts are not detected far from the industries (Tran et al., 2024). Sorting control and impacted areas have been controversial when BACI assessment is conducted (Chevalier et al., 2019). Interpretations should be approached with caution due to limitations in the quality and quantity of data, including variations in satellite imagery, seasonal NDVI fluctuations, cloud cover, and human activities beyond economic zones. However, these factors likely have a negligible impact on overall trends due to geographical homogeneity. Although control areas should not receive any human impact, such areas are not feasible near impacted areas. The main challenge when choosing a control area is the fact that there are very few, if any, remaining areas that aren't affected by human activities (Karr and Chu, 1997). In this study, the control plots also received minimal human impacts. Disturbance rank is likely to solve this issue by analyzing the data quantitatively. Because this quantitative score is implemented to enhance the objectivity of quantitative disturbance classification process for wetlands, including mangroves (Karr and Chu, 1997).

Human activities have impacted mangrove forests worldwide. For example, land resources, including agricultural, mangrove and forest lands, are put at risk in the process of developing economic zones in Myanmar (Aung et al., 2022). In the Vietnamese Southern Coast, NDVI was decreased from 1988 to 2023 due to the conversion of mangroves to built-up areas and waterbodies with the disappearance of mangroves more than 1 km^2 (Tran et al., 2024). In the study area, NDVI declined 6 km^2 on and around the built-up from 2011 to 2021. In the Red Sea, Saudi Arabia, NDVI was reduced due to dredging operations (Arshad et al., 2020).

Road construction exacerbates mangrove loss by altering soil permeability and disrupting hydrological connectivity between mangroves and open water bodies (Ashournejad et al., 2019; Feller et al., 2009). However, hydrological changes seem to affect weakly the mangrove before and after the economic zone construction, as the study area is mostly flat. Marginal mangroves, more accessible to human activity, face greater threats than interior forests (Zhu et al., 2021; Tran et al., 2025). However, in this study, degradation was more pronounced in intermediate forests due to road construction. Given their fragility, mangrove conservation requires rigorous monitoring, but ground-based methods are insufficient. This study demonstrates the effectiveness of BACI assessments and remote sensing for detecting changes in land use.

Beyond infrastructure development, additional factors, including excessive resource extraction, illegal shrimp farming, grazing by cattle and wild deer, and encroachment, have led to ecosystem disruption due to weak regulatory enforcement (Sajjaduzzaman et al., 2005; Ullah et al., 2010; Uddin et al., 2022). These cofounding variables contribute to NDVI reduction, underscoring the need for comprehensive conservation strategies.

The consequence of construction indicates that mangrove ecosystems are not prioritized in the planning and decision-making of the special economic zone design. The conservation of habitat quality determines the structure and function of forests, including mangroves (Zhu et al., 2021). The effects of economic zones were broader than previously thought. Therefore, the large-scale planning of economic zone is required along with the protection against illegal use. We recommend practical conservation strategies, including the incorporation of mangrove buffer zones into economic zone planning and the assessment of road-induced soil permeability.

Conclusion

Mangrove NDVI was analyzed by IKONOS and TripleSat images to assess before-and after-economic zone construction activities from 2011 to 2021. Detection techniques were used to monitor changes in mangrove over the study period. NDVI reduced in the north of the forest close to the economic zone, and NDVI also declined in the intermediate region. The conversion of forest to other land uses led to NDVI decline. Using a BACI assessment, this study identified lower NDVI in the intermediate mangrove area, reconfirming the negative impact of road construction on mangrove health. Infrastructure development, road construction, sand filling and forest clearing for economic zone construction were responsible for these changes. This study underscores the necessity of considering the effects of such activities on mangrove forests using BACI design. Monitoring human interference in surrounding mangroves and implementing strict conservation and reforestation initiatives should be encouraged to protect such fragile ecosystems from further degradation.

The expansion of economic zones in the future is likely to pose significant risks to nearby resources, including mangroves. The findings of this study provide insights for mangrove regions, emphasizing the need for policymakers to assess the environmental consequences of economic zone development in coastal areas. To mitigate adverse effects, strict environmental impact assessments should be implemented prior to adopting such initiatives.

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Conflict of interest The authors declare that they have no conflict of interest.

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Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval No ethical approval was required.

Authors’ contribution statements

IAN: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. TS: Writing – review & editing, Supervision, Validation, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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