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Decadal Trends in Mangrove Cover and Implications for Conservation: A Case Study of Thoothukudi Coast, India (1990-2023)

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PR conducted sampling and wrote original draft of the manuscript. PP conceptualized, designed and supervision of the study, VR, NJ, DM and SA reviewed the draft of the manuscript and supervision of the study. CS Species identification, data analysis and interpretation.

Key words
Mangroves cover, NDVI, Decadal analysis, LULC

ABSTRACT

The present study evaluated mangrove cover and normalized difference vegetation index (NDVI) from 1990 to 2023 in the mangrove ecosystem of the Thoothukudi coast. The land use land cover patterns were obtained with four classifications, viz., water/water bodies, mangrove, terrestrial vegetation / mixed forest and others. In mangrove cover estimation, eight classifications were made for 2023 to understand the impact of anthropogenic activities like water, mangroves, mudflat, barren/deforested land, built-up, agriculture/saltpans and terrestrial vegetation. The mangrove cover estimation results showed mangrove expansion during the period from 2000 to 2023. NDVI maps on the mangrove vegetation and percentage analyses indicated a rising trend from 68.21% in 2000 to 72.6% in 2023. However, there has been an increase in anthropogenic activities resulting in 35.81% of saltpans (1871.07 ha), 14.35% of built-ups (749.49 ha), 2.36% of industries (123.18), 0.73% of barren/deforested (38.22 ha), 0.09% of recreational area (4.48 ha), 5.82% of agriculture plant (303.9 ha) and 1.78% of mudflats (93.1 ha) for the year class 2023. The results of the present study it could be concluded that the vegetation cover in the Thoothukudi coast has increased.

INTRODUCTION

Mangroves are defined as an ecosystem that sustains a diversified community and as the predominant vegetation in saline regions, and are primarily distributed along the tropical countries inhabiting the dynamic interface of land and sea (Ellison *et al*., 1999). Mangroves are also called coastal forests that inhabit the intertidal environment. They are the most important ecosystem in terms of biology because they facilitate the passage of energy between the land and the sea (Ravindran and Rajesh, 2013). Aburto-Oropeza *et al*. (2008) stated that they provide a variety of other advantages to the ecology, including food and material provided for fish, prawns, and crabs. Mangroves are also referred to as "nature's bio shield" because they act as a buffer zone, absorbing wave energy before it reaches the shoreline, decreasing coastal vulnerability, preventing strong waves from eroding soil, and providing invertebrate community habitats (Wang *et al*., 2003). Globally, the total area of mangroves is around 1,37,760 sq. km and it is distributed in 118 countries and territories in the tropical and sub-tropical regions (Giri *et al*., 2011). The mangroves of India comprise around 3% of the global mangrove vegetation and cover an area of approximately 4,639 Sq.km along the nation's coastal states and union territories (Nakhawa *et al*., 2017). The East coast of India has a large mangrove area of around 3,380 sq. km than that of the west coast of around 1,159 sq. km due to the favorable terrain and gradual slope as well as the delta formed by major Indian rivers (Nakhawa *et al*., 2017).

India State of Forest Report (2021) estimates that 4,87,100 ha of mangrove wetlands are supported in India, with 2,75,800 ha (56.7%) located along the country's east coast, 1,14,700 ha (23.5%) along its west coast, and 96,600 ha (19.8%) in the Andaman and Nicobar Islands (Sandilyan, 2014). In India, the estimated mangrove cover area is 4740 sq. km (SFR, 2013), distributed in 9 coastal states and 3 union territories, with a high percentage of cover in Sundarbans, Gujarat, Andaman and Nicobar Islands (44%, 23%, and 13%, respectively) as recorded with the GIS intervention (Kandasamy, 2017). Tamil Nadu's largest

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mangrove forests, covering over 1,000 hectares, are found in the Nagapattinam, followed by Cuddalore, Tanjore, Tuticorin, and Ramanathapuram, respectively with 700, 400, and 100 hectares of mangroves each. The Pichavaram mangrove, which makes up the majority of the mangrove distribution in the Cuddalore district of Tamil Nadu, was designated as a reserve forest in 1987. Its 1,470 ha total area comprises 50 small islands (Srinivasakumar *et al*., 2012). Pichavaram mangrove covers 50% forest, 40% waterways, and 10% sand and mud flats (Krishnamurthy and Jayaseelan, 1981). In Thoothukudi district, the reported coverage of the mangrove area is 3.80 sq. km (India State of Forest Report, 2021). The decline of mangroves in Tamil Nadu is the result of the conversion of mangrove areas into shrimp farms, agriculture, aquaculture, tourism, urban development, over-exploitation increasing human populations, and industrialization (Ghorai *et al*., 2016). Natural disasters like tsunami, cyclone, and global warming cause an extensive amount of loss mangrove ecosystem. Additional problems the depletion of land due to prolonged exposure of coastlines to wave surges, increased erosion, land subsidence, salinization of coastal soils, and a loss in mangrove areas (Srinivasakumar *et al*., 2012). Given this context, the present study, different classes of land usage pattern were identified and the mangrove cover was estimated in Thoothukudi coast. Furthermore, estimated mangrove cover was subjected to decadal analysis from 1990 to 2023 in mangrove ecosystem of Thoothukudi district.

METHODS

Study area

In the present study, mangrove plant species were collected from three sites (S1-Thoothukudi, S2-Palayakayal and S3-Punnakayal) in Thoothukudi district and identified using standard literature available for Tamil Nadu, India (Reddy *et al*., 2007). The sampling was carried out for a one-year period from December 2022 to November 2023. The sampling was carried out with a 5 X 5 m transects, placed at a random distance of 10 m by the zig-zag method as described by Kathiresan and Ajmalkhan (2013). The collected mangrove plant species and its associates were identified, counted, and classified according to the habitat (Kathiresan and Ajmalkhan, 2013). The data from the transect formed the basis for ground truthing and compared with the satellite data for lucid knowledge on mangrove species distribution and its associates. During the sampling, other associated ichthyofauna are also enlisted. The collected fish samples were washed in clean potable water, sorted into taxonomic groups, and preserved in formaldehyde solution (10% in a plastic container) for further analysis. The specimens were identified using standard keys such as FAO and the Fishbase website (Fischer and Bianchi, 1984; Pauly and Froese, 2021; WoRMS).

Mangrove cover estimation and normalized difference vegetation index

In order to study the mangrove cover, time series LANDSAT images were downloaded from USGS earth explorer with less than 20% cloud cover and images with cloudy nature and reflection were neglected (Rani *et al*., 2021). The mangrove cover map was reconstructed to include mining barren lands/ deforested regions, aquaculture systems such as shrimp farms, fish ponds, and saltpans, terrestrial vegetation, sandy beach, mudflats, and estuarine water. The present study also used satellite infomages from LANDSAT series to create the regional level land use land cover maps for the study area at decadal intervals from 1990 to 2020 (Roy *et al*., 2016). The data classifications were generated using the international geosphere-biosphere programme (IGBP) categorization scheme as a guide. In Table I, the IGBP categories correspond to the pixel values in the data provided with this data set. In addition, using the quantum-geographical information system (Q-GIS) computer software package, NDVI maps were digitized for the assessment of mangrove health by normalized difference vegetation index (NDVI).

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

$$NDVI = \frac{(Band\,5 - Band\,4)}{(Band\,5 + Band\,4)}$$

Where, RED and NIR denote spectral reflectance measurements in the visible (red) and near-infrared (NIR) areas, respectively (Green *et al*., 1998; Giri *et al*., 2014). Water bodies, no vegetation cover, low vegetation cover, healthy vegetation cover, and very healthy vegetation cover were all assigned NDVI values (Silva *et al*., 2013). The land use and land cover (LULC) pattern were conducted with five classifications for NDVI analysis, viz., water, no vegetation, low vegetation, moderate vegetation and higher vegetation. In mangrove cover estimation, six classifications were made for the year 2024 to understand the impact of anthropogenic activities like water, mangroves, mudflat, barren/deforested land, built-up, agriculture/saltpans, terrestrial vegetation and sand beach. Different land usage patterns were identified and the mangrove cover was estimated for the Thoothukudi coast as per the procedure's detailed by Heumann (2011). This estimated mangrove cover in estuary ecosystems, Thoothukudi coast was subjected to decadal analysis from 1990 to 2023.

Table I. Classification scheme and description of land use/land cover (LULC) classes.

Pixel value	IGBP classification	Description	Reason attributed
1	Water/water bodies	Surface water bodies in these areas might be fresh or salt water bodies that are either impounded as ponds, lakes, reservoirs, or flow as streams, rivers, etc.	Water spread area of the creek
2	Mangrove	The places between the tides have evergreen forests. There are plenty of halophytic plants in these deep woodlands.	Mangrove cover estimation
3	Terrestrial vegetation/ mixed forest	Trees of woody and sparse leafy vegetation with a percent cover >60% and consists of tree communities with interspersed mixtures or mosaics of the other evergreen (broad leaf and needle leaf) forest, deciduous ((broad leaf and needle leaf) forest, shrubland, grassland types	Adjacent vegetation
4	Others	It includes other mixed group of crop land, built up land, barren land, aquaculture, salt pans, mudflats and sand beaches	Impact various pressure

RESULTS

Estimation of mangrove cover

The study was conducted to evaluate mangrove cover, NDVI from 1990 to 2024 in mangrove ecosystem of Thoothukudi district, Tamil Nadu, Southeast coast of India along with a decadal analysis for resource identification and conservation. The mangrove species observed were *Avicennia officinalis, A. marina, A. alba* and *Rhizophora mucronate* and the associates were *Suaeda maritime, Suaeda australis, Salicornia europaea* and *Salicornia brachiata.* The survey from 108 transects (5 X 5 m) revealed that the solitary stunted mangrove species *Avicennia officinalis* and *A. alba* were prevalent in three stations of Thoothukudi coast. The diversity profile of ichthyofuna revealed common fishes, *Sillago sihama* (Fabricius, 1775), *Stolephorus indicus* (van Hasselt, 1823), *Siganus lineatus* (Valenciennes, 1835), *Terapon jarbua* (Fabricius, 1775), *Hemiramphus far* (Fabricius, 1775), *Sardinella gibbosa* (Bleeker, 1849), and *Mugil cephalus* (Linnaeus, 1758), while crustaceans were *Penaeus monodon* (Fabricius, 1798), *Penaeus indicus* (H. Milne Edwards, 1837) and *Penaeus semisulcatus* (De Haan, 1844), *Scylla serrata* (Forskal, 1775), *Portunus pelagicus* (Linnaeus, 1758) and *P. sanguinolentus* (Herbst, 1783). The identified gastropods are *Cerithium coralium* (Kiener, 1841), *Pirenella Arabica* (Reid, 2016) and *Clypeomorus batillariaeformis* (Habe and Kosuge, 1966), while the predominant bivalves are *Villorita cyprinoides* (Gray, 1825), *Saccostrea cucculata* (Born, 1758), *Donax incarnates* (Gmelin, 1791) and *Meretrix casta* (Gmelin, 1791).

The decadal analysis of land use and land cover for the estimation of mangrove cover (Table II) in these three stations of Thoothukudi coast, Tamil Nadu revealed a mangrove cover of 13.38% in 1990, covering 699 ha,which reduced to 12.08% in 2000, covering 631 ha (Figs. 1–3).

Table II. Decadal analysis of mangrove cover from 1900–2023 in Thoothukudi coast.

Year	Class	Area (ha)	Area (Sq. Km)	%
1990	1	554.8	5.55	10.62
	2	699.0	6.99	13.38
	3	711.8	7.12	13.62
	4	3258.9	32.59	62.38
2000	1	622.8	6.23	11.92
	2	631.0	6.31	12.08
	3	444.8	4.45	8.51
	4	3525.9	35.26	67.49
2010	1	599.8	5.99	11.48
	2	654.0	6.54	12.52
	3	882.8	8.83	16.90
	4	3087.9	30.88	59.10
2020	1	649.8	6.50	12.44
	2	604.0	6.04	11.56
	3	632.8	6.33	12.11
	4	3337.9	33.38	63.89
2022	1	636.3	6.36	12.18
	2	590.5	5.91	11.30
	3	619.3	6.19	11.85
	4	3378.4	33.78	64.66
2023	1	701.3	7.01	13.42
	2	655.5	6.56	12.55
	3	684.3	6.84	13.10
	4	3183.4	31.83	60.93

1, Water; 2, Mangroves; 3, Terrestrial vegetation; 4, others.

However, during 2000 to 2010, mangrove cover increased to 12.52%, occupying 654 ha. This was followed by a decline in mangrove cover during 2010 to 2022 and increasing trend during 2022 to 2023. Likewise, water spread area varied from 636.3 ha in 2022 to 701.3 ha in 2023. Similarly, the area covered under other classifications also showed declining trends from 3525.9 ha (2000), 3087.9 ha (2010), and increasing trend from 3337.9 ha (2020), 3378.4 ha (2022) and 3183.4 ha (2023). The category of others was further classified as area, which includes saltpans (35.81%), built-ups (14.35%), industries (2.36%), barren/ deforested (0.73%), recreational area (0.09%), agriculture plant (5.82%) and mudflats (1.78%) for the year class 2023, which covered 60.94% of land area (Table II).

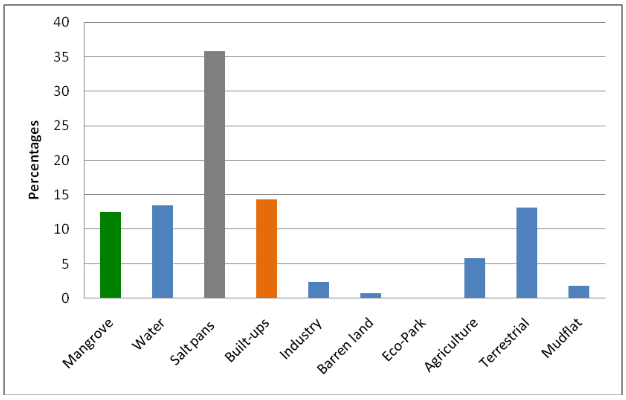

Fig. 1. Mangrove area during 2024 in Thoothukudi coast.

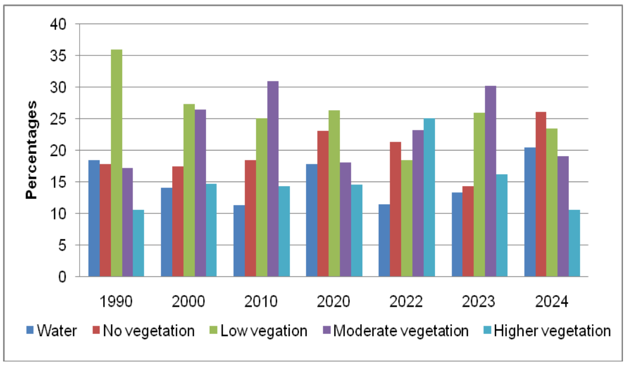

Fig. 2. Normalized difference vegetation index (NDVI) during 1990–2024 in Thoothukudi coast.

Normalized different vegetation index (NDVI)

For studying the NDVI satellite infomages recorded from LANDSAT series were used to create the regional level LULC maps for the study area at decadal intervals from 1990 to 2020. The data classifications were generated using the IGBP categorization scheme as a guide. In addition, NDVI maps were digitized for the assessment of mangrove health by NDVI, using the Q-GIS computer software package. The NDVI map study revealed that the Thoothukudi coast vegetation cover was moderate, after inclusion of low healthy and very healthy vegetation. The estimated index value increased from 63.51% in 1990 to 70% in 2010, which then declined from to 58.67% in 2020, and again increased to 72.09% in 2023 (Table III).

Table III. Mangrove cover in Thoothukudi coast in 2024.

S.	Class	Area (m²)	Area (ha)	%
1	Mangroves	6555000	655.5	12.55
2	Water	7013000	701.3	13.42
3	Saltpans	18710700	1871.07	35.81
4	Built-ups	7494900	749.49	14.35
5	Industries	1231800	123.18	2.358
6	Barren/deforested	382200	38.22	0.732
7	Recreational area	44800	4.48	0.086
8	Agriculture	3039000	303.9	5.817
9	Terrestrial vegetation	6842600	684.26	13.1
10	Mudflat	931000	93.1	1.782

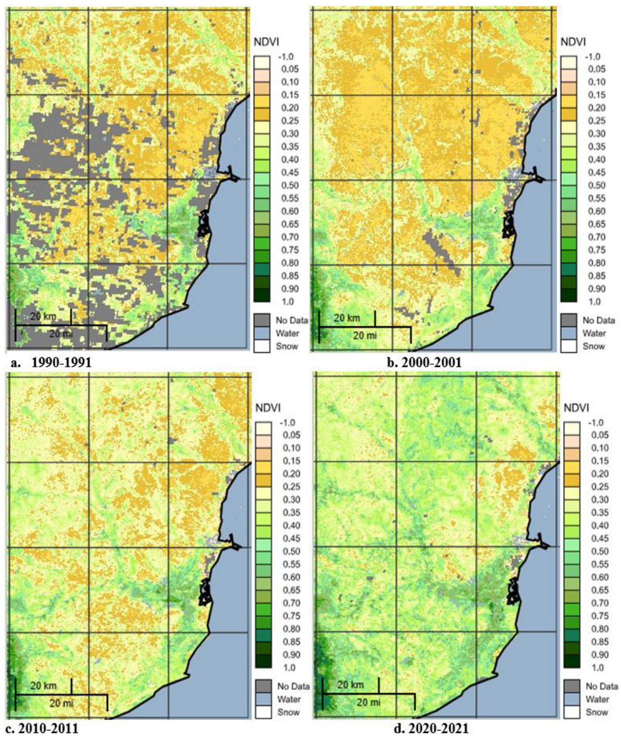

Fig. 3. NDVI during, a, 1990–1991; b, 2000–2001; c, 2010–2011; d, 2020–2021 in Thoothukudi coast.

DISCUSSION

Land use and land cover mangrove cover

At station 1, the stunted growth of *Avicennia* sp. was due to lack of fresh water inflow. In station 2, the brackish water with less salinity and the addition of freshwater from Tamiraparani river might have favoured the growth and development of the mangrove vegetation. The edaphic factor with the micronutrients, rainfall, temperature, humidity and pH of water also favored the growth and development of mangroves. In station 3, *A. alba* was recorded dominantly during the study period. In station 1, the mangrove ecosystem is under significant pollution stress from industrial effluents and anthropogenic activities leads to significant decline in flora and fauna (Keerthana *et al*., 2023). In station 2 and 3, rich flora and fauna was observed when compared to station 1 because its less prone to industrial and anthropogenic activities. *Avicennia marina* and *A. officinalis* were the dominated species in all the three stations, whereas, *Rhizophora mucronata* was observed less dominant in all the three stations. At station 1 and 2, Tamil Nadu Forest Department and started planting of *R. mucoronata* as a restoration measure and found thick vegetation of mangroves at certain places and at some places it was found sparse and patchy. Global Nature Fund (GNF) launched a biodiversity restoration project in Tamil Nadu (India) at Lake Pulicat and started planting mangrove forests by CReNIO, the Non-Governmental Organization (NGO).

Avicennia sp. was recorded in all the three stations due to wide range of salinity, developed in areas subjected to higher evaporation and characterized by higher pore water salinities. Compared with previous studies, Ravindran and Rajesh (2013) documented 4 species of mangroves belonging to 3 genera and 6 species of salt marsh plants belonging to 4 genera, in Punnakayal, Thoothukudi coast; in the present study, *Avicennia marina*, *A. officinalis* and *Rhizophora mucronata* were reported in Punnakayal Mangrove region. Sakthivel *et al*. (2014) observed the dominant of *Avicennia alba* in the Palayakayal estuary. Arunprasath and Gomathinayagam (2014) reported the dominance of *A. marina, A. officinalis, Rhizophora apiculata* and *R. mucronata* in mangrove regions of Pichavaram, Muthupet and Gulf of Mannar of region Tamil Nadu. Daniel et al. (2014) reported finfishes *Arius* sp., *Mugil cephalus*, *Terapon* sp., *Siganus canaliculatus, S. javus, Lutjanus argentimaculatus, Lethrinus* sp. and *Gerres subfasciatus*; shellfishes *Penaeus monodon, P. indicus, P. semisulcatus, Scylla serrata, S. tranquebarica, Portunus pelagicus* and *P. sanguinolentus* in mangrove area of Thoothukudi.

The decadal analysis of land use land cover for the estimation of mangrove cover in Thoothukudi coast revealed mangrove cover of 13.38% in 1990, occupying 699 ha, which reduced to 12.08% in 2000, occupying 631 ha. However, during 2000 to 2010, it increased by 12.52%, occupying 654 ha. Mangrove cover declined during 2010 to 2022 and increased later during 2022 to 2023. The category others were further classified as area, which includes saltpans (35.81%), built-ups (14.35%), industries (2.36%), barren/ deforested (0.73%), recreational area (0.09%), agriculture plant (5.82%) and mudflats (1.78%) for the year class 2023, which covered 60.94% of land area. The area showed declining trend from 3525.9 ha (2000), 3087.9 ha (2010), 3337.9 ha (2020), 3378.4 ha (2022) and 3183.4 ha (2023). This decrease may be due to anthropogenic pressure and mangrove defoliation (Kesavan *et al*., 2021; Sathish *et al*., 2021). Ghorai *et al*. (2016) reported that, the extent of mangroves increased progressively from 5986.20 ha in 1991 to 6421.48 ha in 2000, and it increased to 6756.3 ha in 2014. This increase was caused by plantation, awareness, and coastal zone management plans in mangrove areas along Tamil Nadu. According to Sudhan *et al*. (2023) decadal analysis of land use and land cover for the estimation divulges that the mangrove cover was higher (37.32 %) in 1990, occupying 3265.47 ha, than in 2000, occupying 2375.01 ha in Gorai creek of Mumbai. This present study on decadal analysis of land use land cover in Thoothukudi revealed the reduction in mangrove cover from 1990 (13.38%) to 2000 (12.08%). The primary causes of reduction in the mangrove's cover can be attributed to population pressure, building and development projects, and the conversion of the area into saltpans, farms, and agricultural land (Vijay *et al*., 2005). The estimated mangrove cover and NDVI in the present study, revealed positive correlation in their distribution and subjected to anthropogenic activities. This study suggested strengthening the managerial measures for conservation and protection of this green shield cover along the Thoothukudi coast.

Satellite imagery and NDVI mapping

The NDVI map showed moderate vegetation cover in the Thoothukudi coast, after inclusion of low and well healthy vegetation. The estimated index value showed an increasing trend from 1990 (63.51%) to 2010 (70%), which declined during 2010 (70%) to 2020 (58.67%), and it again showed an increasing trend from 2020 (58.67%) to 2023 (72.09%). Though, the mangrove cover showed an increasing trend, the healthy and moderately healthy vegetation are under anthropogenic pressure of domestic sewage discharge, industrial disposal, plastic pollution, coastal urbanization and minor natural incidents. Changes in the mangrove vegetation over these 90 years, *i.e.*

decrease in area due to anthropogenic practices and change in microtopography, an increase in area due to conservation and restoration practices, are also being monitored by the local community (Gnanappazham and Selvam, 2011). Vaghela *et al*. (2018) reported around 38% and 27%, respectively in Gulf of Kachchh, India can be categorized as very-healthy and healthy. Sudhan *et al*. (2023) studied mangroves in Gorai creek, Mumbai and observed the trend of NDVI declined from 1990 (41.42%) to 2000 (34.06%), and increased from 2010 onwards. The monsoon season and its commencement are regarded as the best times of year for the development and growth of vegetation. The study's outcome provided strong evidence for this assertion, showing that the thick mangrove area from 1996 has grown to a level of extremely dense mangrove in 2016 (Kripa *et al*., 2019). Converting the range of moderately dense mangroves to dense mangroves occurred simultaneously. From the decadal analysis in the present study, it could be observed that the area under the built-ups increased from 1990 to 2024. This may be the result of an increasing demand for housing in opposition to population expansion. The reason for the decline in the open mangrove class between 2010 and 2020 is because young mangroves older than three years have developed into thick mangroves, a stage typically reached by trees that are around ten years old. The Forest Survey of India established that the planting of new mangrove and conservation measures implemented throughout during 1990s were responsible for the rise in open mangroves (ISFR, 2021).

CONCLUSIONS

Threats to this Thoothukudi mangroves include infrastructure, pollution and climate change. Urgent conservation efforts are necessary to mitigate these impacts. This research informs policymakers on sustainable management strategies, ecotourism, ecosystem modeling, biodiversity assessment and ecosystem health evaluation, emphasizing continuous monitoring and time-series analysis for effective conservation.

DECLARATIONS

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Ethical approval

No animals were harmed during the entire research.

Generative AI and AI-assisted technology statement

The authors have declared that no generative AI or AI-assisted technologies were used to create this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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