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Transforming Mangrove Monitoring into Digital Climate Learning: A Spatiotemporal Insight from Bengkulu City, Indonesia

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Abstract

This study investigates how mangrove monitoring can be converted into a digital learning resource to enhance climate literacy. Focusing on Bengkulu City, Indonesia, the research combines remote sensing analysis with digital pedagogy to provide a spatiotemporal view of changes in the mangrove ecosystem. Multi-temporal satellite data from 1995, 2005, 2015, and 2025 were analyzed using Random Forest classification to identify patterns of mangrove loss, stability, and regrowth. The findings indicate a 57.3% decline in mangrove vegetation cover from 1995 to 2025, with some recovery observed after 2015 due to local restoration efforts. By integrating GIS, the spatial data was transformed into an interactive digital module that allows learners and community members to explore climate-related changes more intuitively. Evaluation of the module revealed an average learning improvement of 25%, particularly in spatial reasoning and understanding of climate-ecosystem relationships. The results demonstrate that converting ecological data into digital educational media can connect scientific knowledge with public awareness, positioning mangrove monitoring as both a conservation initiative and a tool for climate-resilient education.
Keywords: Mangrove Monitoring; Spatiotemporal Analysis; Digital Climate Learning; Bengkulu City; Remote Sensing.

Introduction

Coastal ecosystems, including mangroves, hold substantial ecological and educational significance. They provide natural protection against coastal erosion and extreme weather events, while also serving as carbon-rich systems that help mitigate global warming (Alongi, 2020; Basyuni et al., 2022). Beyond their ecological advantages, mangroves function as "living laboratories" for sustainability education, integrating scientific knowledge, local practices, and environmental ethics (Najwa & Suhartini, 2023). Despite their critical importance, these ecosystems are currently facing unprecedented threats from land reclamation, aquaculture expansion, and rapid coastal urbanization (Friess et al., 2019; Nguyen et al., 2024). Indonesia, which harbours nearly one-quarter of the world's mangrove forests, continues to experience significant losses despite extensive rehabilitation efforts. This situation underscores persistent challenges in ecological management and public environmental literacy (Arifanti, 2020; Kusumaningtyas et al., 2021; Basyuni et al., 2023).

Bengkulu City, situated on Sumatra's southwestern coast, exemplifies these global challenges. Over the past three decades, the mangrove ecosystems in Sungai Serut, Pulau Baai, and Teluk Sepang have experienced significant degradation due to port expansion, waste disposal, and urban development. While spatial analyses utilizing remote sensing data have documented these declines (Giri et al., 2011; Soeprobowati et al., 2022; Wang et al., 2023). The majority of research has concentrated on technical aspects, prioritizing land cover metrics over the transformation of spatial data into educational resources aimed at enhancing climate awareness among the public and students (Fauville et al., 2024; (Birdsall, 2021). Recent advancements in digital pedagogical approaches and geospatial learning environments offer new opportunities to bridge existing educational gaps. By incorporating remote sensing and GIS data into online educational platforms, students can visualize ecological transformations, analyse spatial patterns, and comprehend the connections between human activities and environmental resilience (Semken & Freeman, 2008). This approach is consistent with UNESCO's (2023) promotion of digital education, which underscores the importance of cultivating sustainability skills through genuine, data-driven learning experiences. Such integration holds the potential to transform geography education. Geography students are not just map readers; they are future educators and analysts who must interpret the spatial narratives of environmental change. Engaging with real-world mangrove monitoring data enables students to connect geospatial evidence with socio-ecological processes like urban expansion, sedimentation, and restoration (Utami et al., 2025). Interactive GIS modules equip students to enhance spatial reasoning skills, apply critical environmental analysis, and improve digital literacy for climate-focused education.

Integrating mangrove monitoring datasets into digital climate education modules significantly enhances environmental comprehension and cultivates the practical skills essential for future geography educators. This approach enables educators to incorporate satellite data and tools such as Google Earth Engine and ArcGIS Story Maps into their curriculum, thereby facilitating student engagement and inquiry-based learning. This research examines the incorporation of mangrove monitoring into digital climate education, using Bengkulu City as a case study. The study specifically aims to: (1) Analyse the spatiotemporal changes in mangrove vegetation cover from 1995 to 2025, and (2) Assess the educational impact of utilizing these spatial datasets in interactive GIS-based learning to enhance digital climate literacy among geography students. By combining scientific visualization with educational innovation, this study advances the understanding of mangrove ecosystems. It transforms climate-focused teaching, establishing digital learning as a practical link between ecological data and human comprehension.

Methods

Study Area

The research was conducted in the coastal region of Bengkulu City, located on the southwest coast of Sumatra, Indonesia (3°45′–3°55′ S; 102°15′–102°25′ E). This area is characterized by tidal estuaries, dense mangrove forests, and a tropical monsoon climate, with an annual rainfall of approximately 2,700 mm. Mangrove ecosystems are predominantly situated in the sub-districts of Sungai Serut, Pulau Baai, and Teluk Sepang, where anthropogenic activities such as port development, aquaculture, and urban expansion have significantly altered the coastal environment. These sites were selected to represent spatial variations in both degradation and restoration processes, providing optimal conditions for integrating ecological observations with digital learning modules. Figure 1 depicts the location of the study area and the distribution of mangroves along the coast of Bengkulu.

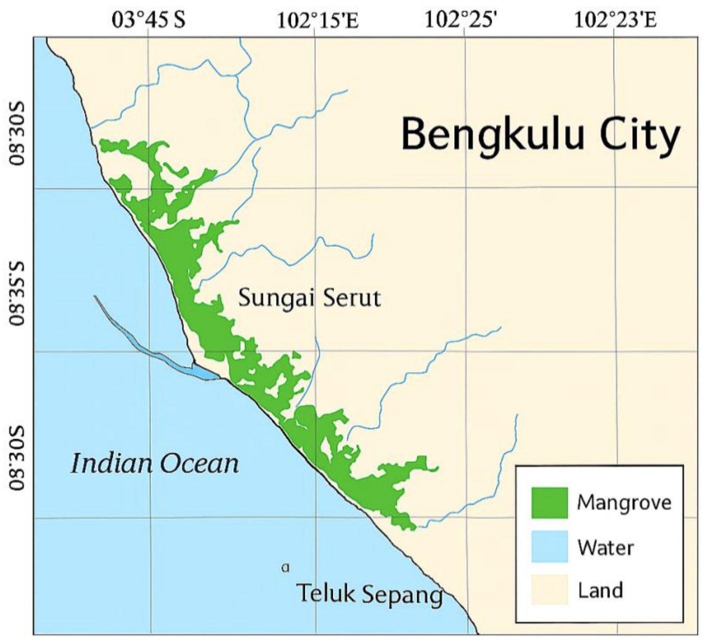

Figure 1. Map of Study Area and Mangrove Distribution (Bengkulu City, Indonesia)

Data Sources and Image Processing

To assess temporal changes in mangrove cover, multi-temporal satellite images were acquired for the years 1995, 2005, 2015, and 2025. The data were processed using Google Earth Engine (GEE) with a combination of spectral indices and machine learning classification.

Table 1: Satellite Imagery Datasets and Parameters Used for Analysis

Satellite Sensor	Acquisition Year	Spatial Resolution (m)	Key Bands/Indices	Data Source
Landsat 5 TM	1995	30	NDVI, NIR–Red	USGS Earth Explorer
Landsat 8 OLI	2005, 2015	30	NDVI, SWIR–Red	USGS Earth Explorer

Sentinel-2 MSI	2025	10	NDVI, NDMI, NIR–SWIR	Copernicus Open Hub

To ensure spectral consistency, all images were subjected to radiometric and atmospheric corrections using the Dark Object Subtraction (DOS1) method. The normalised difference vegetation index (NDVI) was used to distinguish between vegetated and non-vegetated areas. The Random Forest (RF) algorithm was chosen for classification because of its effectiveness in managing mixed pixels and spectral variability (Wang et al., 2023). The classification accuracy was assessed utilizing a confusion matrix and the Kappa coefficient, yielding values ranging from 0.82 to 0.87. These results indicate a high level of reliability in the classification process.

Change Detection Analysis

To assess the temporal variations in mangrove vegetation during the periods 1995–2005, 2005–2015, and 2015–2025, a post-classification comparison methodology was utilized. The resulting maps were categorized into three classifications: Loss (Degradation), indicating areas converted for alternative land uses; Stable (Persistence), representing mangrove regions that have remained unchanged; and Regrowth (Restoration), signifying areas where vegetation has shown signs of recovery. The substantial decline observed from 1995 to 2005 was associated with port development and land reclamation activities. Conversely, the improvement noted post-2015 is attributed to the efficacy of community-driven rehabilitation initiatives led by local NGOs and universities (Halim, 2021; Kusumaningtyas et al., 2023).

Development of Digital Climate Learning Modules

The educational component of this research sought to transform ecological data into engaging learning experiences for Geography students. The initiative incorporated classified maps, spatial statistics, and time-series analyses into an online GIS module utilizing ArcGIS Story Maps and Google Earth Engine Apps. The module comprises three distinct learning stages. The initial stage is observation, in which students examine temporal and spatial variations in mangrove ecosystems. The subsequent stage is interpretation, during which students analyse the underlying causes of these variations. The final stage, reflection, involves linking local ecological changes to broader climatic impacts. This approach adheres to the "enquiry–analysis–reflection" framework proposed by Semken and Freeman (2008), promoting experiential and digital sustainability education. The study involved 30 geography students from the Geography Education Study Program, Faculty of Teacher Training and Education, Universitas Prof Dr Hazairin SH, Indonesia, providing insights from an academic perspective.

Evaluation of Learning Outcomes

To measure the effectiveness of digital learning integration, a pre-test and post-test design was conducted, focusing on three indicators of *digital climate literacy*:

(a) Spatial interpretation skills,

(b) Climate–ecosystem understanding, and

(c) Digital literacy competence.

The evaluation employed descriptive statistics and paired-sample t-tests to assess the significance of improvement.

Results and Discussion

Spatiotemporal Dynamics of Mangrove Vegetation (1995–2025)

The classification results indicated notable changes in the spatial and temporal patterns of Bengkulu's mangrove cover over the thirty years from 1995 to 2025. Table 2 illustrates a significant reduction in the total mangrove area. Between 1995 and 2015, the area decreased from 283.21 hectares to 84.05 hectares, representing a 70% reduction. This significant decrease occurred when ports were built and settlements grew around Pulau Baai and Teluk Sepang. However, from 2015 to 2025, the mangrove area grew to 120.93 hectares, a 43.9% increase. This growth was due to local efforts to restore mangroves and increased community involvement in managing the coast.

Table 2: Mangrove Vegetation Cover Change From 1995 to 2025

Year	Area (ha)	Change (ha)	Change (%)
1995	283.21	–	–
2005	93.81	-189.40	-66.9
2015	84.05	-9.76	-10.4
2025	120.93	+36.88	+43.9
Total (1995–2025)		**-162.28**	**-57.3**

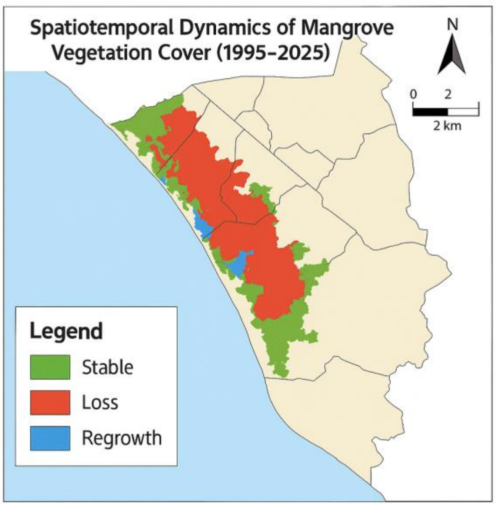

Figure 2. Spatiotemporal Dynamics of Mangrove Vegetation Cover in Bengkulu City (1995-2025)

Figure 2 presents the thematic map illustrating changes in mangrove cover over three decades, highlighting distinct patterns of loss and regrowth. This pattern underscores the persistent impact of anthropogenic pressures as the primary drivers of change. Recovery trends illustrate the effectiveness of community-led restoration initiatives and the implementation of local policies. The areas of regrowth, primarily situated near river estuaries and buffer zones, align with regions targeted by replanting efforts spearheaded by universities and supported by NGOs (Srifitriani et al., 2020; Kusumaningtyas et al., 2023). These findings corroborate broader research in Southeast Asia, illustrating that community engagement, when combined with spatial monitoring and adaptive management, can reverse decades of mangrove degradation (Friess et al., 2020).

Quantitative Change and Spatial Distribution

Spatial analysis confirmed a total net loss of 162.28 ha (57.3%) from 1995 to 2025. The most substantial reduction, totalling −189.4 hectares, occurred between 1995 and 2005, coinciding with the industrial expansion phase of Bengkulu Harbor. In contrast, a positive net change was recorded from 2015 to 2025, with a regrowth of +36.88 hectares, indicating that mangrove recovery began to exceed deforestation in certain sub-districts. Figure 3 presents the bar chart visualization of mangrove area changes, showing three distinct temporal phases:

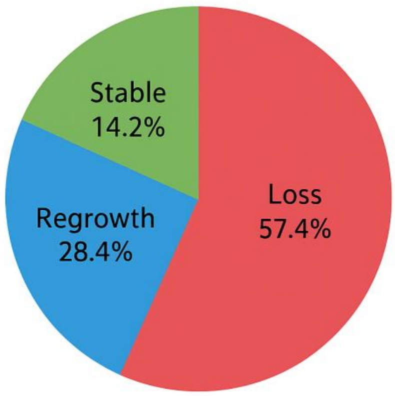

Figure 3. Changes in Mangrove Vegetation Cover in Bengkulu City, Indonesia (1995-2025)

The findings illustrate the capacity of long-term Earth observation data to furnish tangible evidence of landscape transformation, thereby underscoring the significance of remote sensing in the management of coastal ecosystems (Farooqi et al., 2022; Wang et al., 2023).

Pedagogical Interpretation: From Data to Digital Literacy

The spatial maps and datasets generated in this study were transformed into an interactive GIS-based learning module designed to enhance digital climate literacy among geography students. This module enables users to investigate environmental changes over several decades, analyse the underlying causes, and assess the implications for local sustainability. The evaluation results (Table 3) indicate a significant improvement in understanding across all three measured indicators:

a. Spatial interpretation skills increased from 58.4% to 83.7%.

b. Climate ecosystem understanding improved from 61.2% to 86.5%.

c. Digital literacy competence rose from 64.7% to 89.1%.

Table 3: Comparison of Pre-Test and Post-Test Results

Indicator	Pre-Test Mean (%)	Post-Test Mean (%)	Δ (%)	Interpretation
Spatial interpretation	58.4	83.7	+25.3	Significant increase
Climate–ecosystem understanding	61.2	86.5	+25.3	Significant increase
Digital literacy competence	64.7	89.1	+24.4	Significant increase
Overall average	**61.4**	**86.4**	**+25.0**	**High improvement**

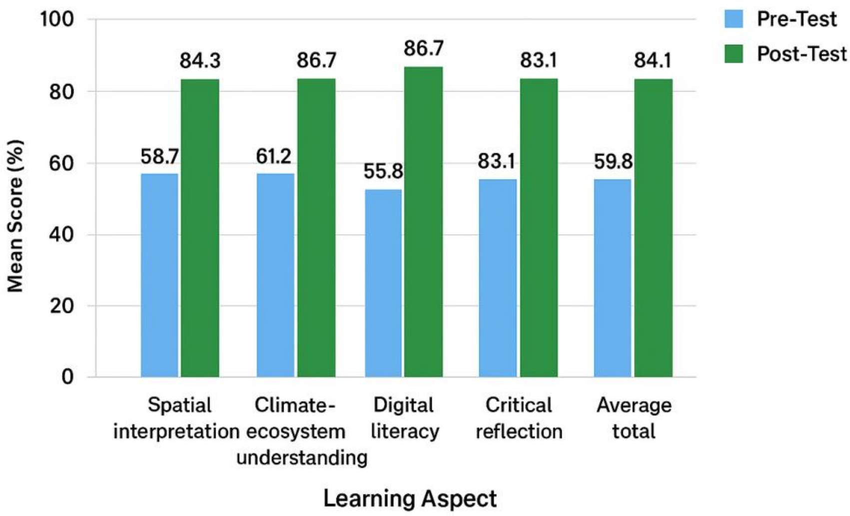

Figure 4. Pre-Test and Post-Test Results on Digital Climate Literacy (n = 30)

Figure 4 illustrates these educational advancements through comparative visualisation. The findings demonstrated a consistent 25% improvement in participants' digital climate literacy, suggesting that integrating real spatial data into online platforms effectively merges scientific content with pedagogical methodologies. These outcomes are consistent with prior research demonstrating that digital environmental learning enhances both cognitive and affective engagement with sustainability topics (Fauville et al., 2024). In geography education, experiential and data-driven learning methodologies substantially enhance students' capacity to interpret spatial relationships and apply scientific reasoning to real-world contexts.

Educational Implications for Geography Education

Integrating spatiotemporal mangrove data into digital learning modules offers numerous educational benefits for geography programs. Authentic Learning: Students engage directly with real satellite data, enabling them to visualize environmental changes within their local regions.

a. Development of Spatial Thinking: Learners engage in the examination of geospatial patterns, thereby enhancing their critical spatial reasoning, which is essential for achieving geographic literacy.
b. Enhancement of Digital Competency: The utilization of tools such as ArcGIS Story Maps and Google Earth Engine enhances students' proficiency in digital mapping and environmental modelling.
c. Strengthening of Climate Literacy: By integrating local data with global climate narratives, students gain a comprehensive understanding of ecosystem resilience.

This approach is consistent with the Inquiry–Analysis–Reflection model, which guides students from observing evidence to interpreting processes and considering their social responsibility (Semken & Freeman, 2008). It also aligns with the UNESCO (2023) framework for digital sustainability education, which emphasizes participatory and community-focused learning.

Table 4: Pedagogical Contributions of Digital Mangrove Monitoring for Geography Students

Learning Domain	Description	Example Activity
Spatial Thinking	Analysing spatial-temporal mangrove change	Time-series NDVI interpretation
Critical Reasoning	Evaluating socio-ecological drivers	Scenario-based discussions
Digital Literacy	Using GIS and web maps	ArcGIS Story Maps dashboard
Reflective Awareness	Linking data to stewardship	Local action mapping projects

Conclusion

This research highlights the innovative potential of combining spatiotemporal mangrove monitoring with digital learning platforms to bridge environmental science and climate education. Between 1995 and 2025, Bengkulu City experienced a 57.3% reduction in mangrove area, leading to a loss of 162.28 ha. This decline is primarily attributed to urban expansion and increased coastal development. However, the regrowth observed since 2015 indicates the growing success of community-driven rehabilitation initiatives and localised restoration strategies.

Beyond ecological evaluation, this study emphasizes the transformative educational potential of converting scientific data into impactful learning experiences. By incorporating genuine satellite imagery, NDVI analysis, and temporal change detection into interactive GIS modules, geography students were able to: visualize actual environmental changes, enhance their spatial interpretation and analytical reasoning, and improve their digital and climate literacy skills by an average of 25%.

The findings indicate that implementing data-driven and enquiry-based learning methodologies significantly enhances students' comprehension of climate ecosystems. Moreover, these methodologies enhance students' environmental awareness and sense of responsibility. This approach equips future geography teachers with practical tools to address sustainability issues through spatial evidence, an essential skill for enabling citizens to adapt to and withstand climate challenges.

The Bengkulu case exemplifies a replicable model for other coastal regions, illustrating how universities can convert ecological monitoring into a participatory learning ecosystem. The findings indicate that for education policymakers and curriculum developers, incorporating geospatial data and digital storytelling tools into higher education curricula can significantly enhance both academic performance and civic engagement in climate action. Future research should extend this framework to encompass broader blue carbon ecosystems and incorporate advanced visualization technologies, such as augmented reality (AR) or AI-driven dashboards, to facilitate immersive environmental learning experiences.

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