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Accelerated invasion of *Nypa fruticans* during 2000-2024 in degraded mangrove ecosystem in Sumatra analysed using Google Earth Engine

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Abstract. *Eddy S, Setiawan AA, Milantara N, Rahmawati, Billardi A, Sundoko A. 2026. Accelerated invasion of* Nypa fruticans *during 2000-2024 in degraded mangrove ecosystem in Sumatra analysed using Google Earth Engine. Biodiversitas 27 (1): d270110. https://doi.org/10.13057/biodiv/d270110.* This study analyzes the invasion patterns of nipah (*Nypa fruticans*) and their implications for the degradation of the Air Telang Protected Forest (ATPF) ecosystem from 2000 to 2024. Using a unique methodological combination of large-scale, time-series analysis from Google Earth Engine (GEE) with high-resolution drone-based validation, we mapped land cover changes and quantified nipah expansion under intensifying anthropogenic pressures. Land cover classification from 2000, 2012, and 2024 revealed a sharp decline in native primary and secondary mangrove forests, concurrent with rapid increases in nipah-dominated areas, open lands, and plantations. This methodology allowed for a more comprehensive tracking and understanding of the invasion dynamics throughout the 2000-2024 timeframe. The Maximum Entropy algorithm was utilized to model the species' potential spread based on key environmental variables, including soil type, Normalized Difference Vegetation Index, elevation, slope, temperature, and rainfall. The results show a significant decline in native mangrove cover, directly corresponding to an increase in nipah colonies and open areas, driven by anthropogenic activities such as illegal logging and land clearing. Between 2000 and 2024, the total area of primary and secondary mangroves decreased significantly, while the invasive nipah population experienced a nearly fivefold increase. Specifically, measurements show the loss of primary mangrove forest exceeded 50% during this period. This expansion was particularly dramatic during the 2012-2024 period, marking an acceleration of the invasion. These ecological transformations not only threaten biodiversity but also substantially diminish the forest's carbon sequestration capacity, undermining regional climate mitigation efforts. Integrated management-combining policy enforcement, restoration of native mangroves, and community-based control of nipah-is urgently needed to restore ecological function and prevent further ecosystem collapse, which provides an urgent warning for conservation policy.

Keywords: Degraded mangrove forest, Google Earth Engine (GEE), invasive species, *Nypa fruticans,* remote sensing

INTRODUCTION

Mangrove forests, with their rich biodiversity and vital ecological roles, serve as natural guardians of coastal areas. These forests are globally recognized as one of the most productive and biologically important ecosystems, serving as a critical interface between terrestrial and marine environments. These crucial ecosystems provide an array of essential services, including protecting coastlines from erosion and storms, providing habitats for diverse aquatic and terrestrial species, and sequestering substantial amounts of carbon (Friess et al. 2019; Cooley et al. 2022). However, anthropogenic activities have degraded mangrove forests across the globe (Almond et al. 2020; Sasmito et al. 2023). This destruction not only diminishes mangrove coverage but also triggers shifts in species composition, notably the invasion of pioneer species such as nipah (*Nypa fruticans* Wurmb). This invasive phenomenon frequently signals ecosystem degradation and can jeopardize the sustained ecological functions of mangroves (Gallardo et al. 2024; Rahman et al. 2024).

The Air Telang Protected Forest (ATPF) in South Sumatra Province, Indonesia, exemplifies a mangrove ecosystem that faces severe threats from degradation. Prior studies consistently demonstrate that the forest has experienced significant degradation and drastic land cover change, resulting in a mosaic of open areas, various plantations, and settlements interspersed with remnant native mangroves (Eddy et al. 2017; 2019; 2021a; 2022). These widespread alterations are primarily anthropogenic, driven by land conversion for agriculture and housing, which contributes directly to carbon stock loss and heightened ecosystem vulnerability (Eddy et al. 2021b; 2023a).

A prominent consequence of mangrove degradation is the extensive invasion of nipah, which exhibits remarkable adaptability to disturbed areas and frequently dominates degraded conditions (Eddy and Basyuni 2020; Moudingo et al. 2020; Numbere and Moudingo 2023). The prevalence of this palm fundamentally alters native mangrove community structures, diminishing biodiversity, and impacting ecosystem functions (Numbere 2019a; Barenblitt et al. 2024). Although nipah has potential for utilization (Wijana et al. 2023; Eddy et al. 2025), its aggressive growth displaces native species in disturbed habitats (Widodo et al. 2020), requiring rigorous monitoring and management efforts based on the understanding of its dispersal dynamics (Eddy et al. 2024a, b).

Remote sensing is crucial for monitoring extensive shifts in land cover (Hu et al. 2020; Farzanmanesh et al. 2024), yet prior research on nipah invasion in degraded areas such as the ATPF has been limited by a lack of continuous temporal data and insufficient high-resolution imageries complemented with validation at the local scale. While the Google Earth Engine (GEE) platform has proven effective for mapping broad-scale mangrove changes (Gorelick et al. 2017; Yancho et al. 2020; Ghorbanian et al. 2021; Islam et al. 2025), a key research gap remains in long-term, high-resolution monitoring of localized degradation and its link to invasive species. This study addresses that gap by pioneering a hybrid methodology, i.e. combining the broad analytical power of GEE with the fine-scale precision of drone imagery. This innovative approach provides a robust model for accurately quantifying nipah's spread and its correlation with human disturbance, offering a deeper understanding of ecological shifts in threatened coastal ecosystems.

This study analyzes the distribution patterns and impact of nipah invasion on mangrove forest degradation by mapping nipah populations using large-scale time-series analysis from GEE. The main novelty of this study, which has not been addressed in previous research, lies in the unique combination of GEE with detailed field validation of high-resolution aerial imagery captured by drones, allowing for a more comprehensive understanding of the invasion dynamics from 2000 to 2024. We hypothesize that (i) Extensive anthropogenic disturbances in the Air Telang Protected Forest have created ecological conditions that favor rapid expansion of *N. fruticans*; (ii) Environmental variables such as soil type, NDVI, and hydrology are significant predictors of nipah distribution; and (iii) Combining long-term satellite analysis with drone-based validation will improve detection accuracy and provide a more reliable assessment of invasion dynamics than either method alone. The results are expected to provide crucial insights into invasion patterns, offering a strong scientific foundation for conservation efforts and government policies aimed at sustainable mangrove forest rehabilitation in the region.

MATERIALS AND METHODS

Study area description

The study was conducted in the Air Telang Protected Forest (ATPF), locally named as Hutan Lindung Air Telang, located in Banyuasin District, South Sumatra, Indonesia (Figure 1). The study area is managed by FMU Unit I Banyuasin (KPHL) under the South Sumatra Provincial Forestry Service. This mangrove ecosystem covers 12,660.87 ha but has been heavily degraded by conversion to plantations, agriculture, settlements, and fishponds, leaving only about 20% of the primary forest (Eddy et al. 2024a). It is bordered by the Bangka Strait and Banyuasin River to the north, Muara Telang Sub-district to the south, Muara Telang and Banyuasin II Sub-districts to the east, and the Banyuasin River to the west. Nearby seaports (two operating at Tanjung Api-api and one under construction at Tanjung Carat) add further pressure. The degraded condition also makes the area highly susceptible to invasion, particularly by nipah, which has spread across most zones from the shoreline to inland.

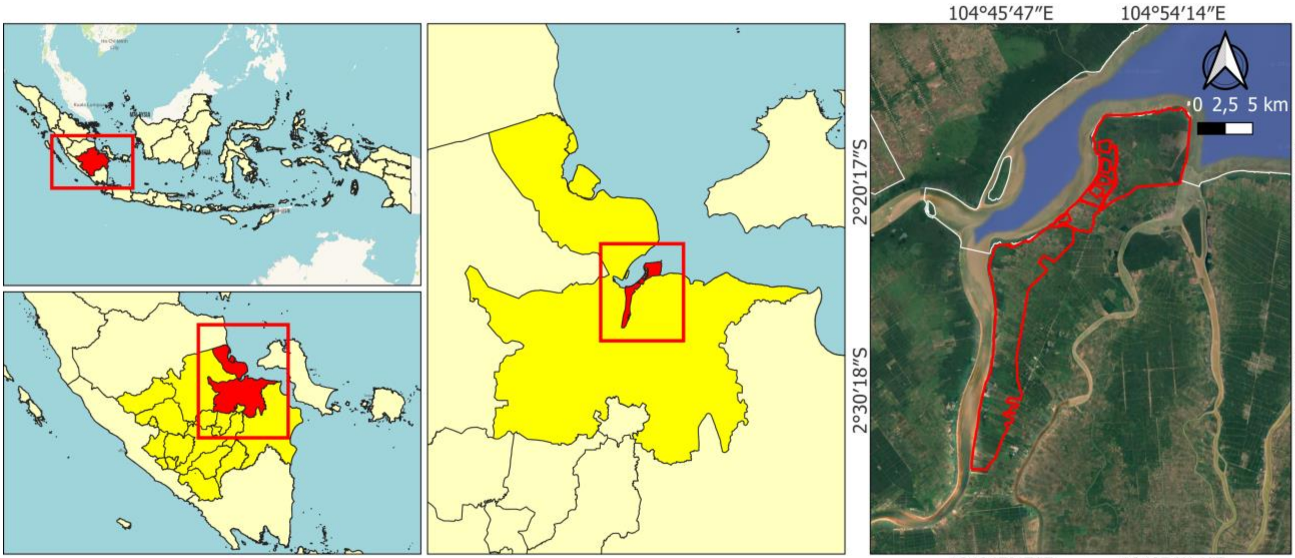

Figure 1. The study area is situated within the Air Telang Protected Forest (ATPF) in Banyuasin District, South Sumatra, Indonesia

Table 1. Multispectral environmental data, including soil type, NDVI (Normalized Difference Vegetation Index), elevation, slope, temperature, and rainfall, detailing each variable's acquisition period, value range, source, and spatial resolution

Environmental data	Acquisition period	Value range	Sources	Bands	Resolution (meters)
Soil type	January 1950 to January 2018	Loamy (1st to 4th class)	Open Land Map Soil Texture Class (United States Department of Agriculture/USDA System)	Multispectral	250
NDVI	June to July (2000, 2012, 2024)	0.65 to 0.9	USGS Landsat 5 TM Collection 2 Tier 1 Raw Scenes (2000); USGS Landsat 7 Collection 2 Tier 1 and Real-Time data Raw Scenes (2012); USGS Landsat 8 Collection 2 Tier 1 and Real-Time data Raw Scenes (2024)	Multispectral	10
Elevation	11 February 2000 to 22 February 2000	-1 to 28 m	NASA SRTM Digital Elevation	Multispectral	30
Slope	11 February 2000 to 22 February 2000	0 to 14.14°	NASA SRTM Digital Elevation	Multispectral	30
Temperature	January to December (2000, 2012, 2024)	27.38 to 29.68℃ (2000); 28.02 to 30.72℃ (2012); 26.81 to 30.54℃ (2024)	MOD11A1.061 Terra Land Surface Temperature and Emissivity Daily Global	Multispectral	1,000
Rainfall	January to December (2000, 2012, 2024)	2871.06 to 2961.75 mm (2000); 2589.07 to 2672.63 mm (2012); 2729.94 to 3165.28 mm (2024)	CHIRPS Daily: Climate Hazards Center InfraRed Precipitation with Station Data (Version 2.0 Final)	Multispectral	5,566

The study area is officially managed by the Forest Management Unit (FMU) Unit I Banyuasin (locally known as *Kesatuan Pengelolaan Hutan Lindung* - KPHL), which operates under the South Sumatra Provincial Forestry Service. This mangrove ecosystem spans approximately 12,660.87 ha but has experienced significant degradation due to extensive land conversion into plantations, agriculture, settlements, and fishponds, sparing only about 20% of the primary forest (Eddy et al. 2024a). Geographically, the forest is bordered by the Bangka Strait and Banyuasin River to the north, the Muara Telang Sub-district to the south, the Muara Telang and Banyuasin II Sub-districts to the east, and the Banyuasin River to the west. The presence of nearby seaports (two operational in Tanjung Api-api and one under construction in Tanjung Carat, north of the Protected Forest) exerts pressure on the area. As a degraded system, the region is highly vulnerable to invasion by robust species such as nipah, which has currently spread throughout nearly every zone, from the shoreline to the inland areas.

Data collection

The research methodology combined satellite-based remote sensing and on-the-ground data, using a novel approach in ecological monitoring. We used satellite imageries from 2000, 2012, and 2024, which were accessed and processed using the Google Earth Engine (GEE) platform. GEE was chosen for its robust capability to analyze large-scale geospatial data efficiently over extended periods, making GEE an ideal tool for monitoring long-term land cover changes (Gorelick et al. 2017).

To complement the broad-scale analysis from satellite imagery, we conducted field surveys from June to July 2025 to verify the presence of nipah colonies. During our field surveys, a DJI Phantom 4 Pro drone captured high-resolution aerial photographs. This imagery provided fine-scale habitat characterization and precise nipah patch locations, which were used as presence data to train distribution models. The data can be categorized into two main types: nipah presence data and environmental variable data. Nipah presence data were gathered through direct field surveys and drone flights, whereas the environmental variable data were sourced from various satellite images (Table 1).

Data analysis

Nipah distribution modeling

Nipah distribution was modeled using the Maximum Entropy (MaxEnt) algorithm, implemented on the GEE platform. This approach identifies the relationships between known locations of nipah presence-derived from field surveys-and a set of relevant environmental variables to predict the species' potential distribution. To ensure resilient and accurate modeling, we configured the MaxEnt algorithm with specific settings. The regularization multiplier was set to 1.0 to balance the model complexity and the predictive performance. We used feature classes, including linear, quadratic, product, and hinge, to capture the non-linear relationships between nipah presence and environmental variables. The model was trained with 500 iterations, providing ample time for the algorithm to converge and optimize its parameters.

The MaxEnt model performance was validated using the Area Under the Curve (AUC) values derived from the Receiver Operating Characteristic (ROC) curve. The model demonstrated very good performance with a mean training AUC value of 0.915 and a mean testing AUC value of 0.898. These values indicate that the model possesses a strong predictive power and a high degree of model confidence in predicting the potential distribution of nipah. Specifically, the minor difference between the training and testing AUC values (typically less than 0.05) confirms that the model is stable and avoids overfitting.

GEE's powerful cloud computing environment was instrumental in this process, allowing us to process the vast geospatial data catalog efficiently and execute complex predictive modeling. We evaluated the performance of the model using area-under-the-curve values. An area under the curve close to 1.0 indicates excellent model performance, such that the predictions of the model align well with the actual presence and absence of the species. This methodology has proven highly effective for monitoring trends and predicting the spatial distribution of specific plant species, including invasive ones (Huang et al. 2024; Wang et al. 2025).

To perform our land cover classification, we used the Random Forest algorithm within the GEE platform, a choice based on its robust performance with multi-temporal satellite data. Using a confusion matrix, we rigorously evaluated the accuracy of our land cover maps for each time point, achieving consistently high Kappa coefficients that confirm the reliability of our long-term analysis. Specifically, the maps for 2000, 2012, and 2024 showed strong overall accuracies of 92.5%, 90.1%, and 94.8%, respectively, with corresponding Kappa coefficients of 0.89, 0.86, and 0.92. This high accuracy was fundamental to our ability to quantify precisely the degradation of native mangroves and the subsequent aggressive expansion of the nipah population throughout the study period.

Nipah occurrence data

Nipah occurrence data were collected via a field survey from June to July 2025. This data consisted of GPS (Global Positioning System) coordinates to mark the locations where nipah were found within and surrounding the landscape under study. These points were then uploaded to GEE to serve as training data for the MaxEnt algorithm, forming the basis for the analysis of nipah's environmental variables.

Environmental variables

Soil data were derived from the OpenLandMap Soil Texture Class satellite imagery, sourced via the Soil Data Access (SDA) System. The data were processed specifically to identify loamy soil, which is generally considered a suitable substrate for nipah growth (Weiss et al. 2016; Numbere 2019b; Hossain et al. 2024). The NDVI was used to indicate vegetation health and density. NDVI data for 2024 were sourced from Landsat 8 imagery, while data for 2012 came from Landsat 7, and the data for 2000 came from Landsat 5. The NDVI was calculated using the formula:

$$NDVI = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

Where, NIR: Represents the reflectance in the near-infrared band, Red: Represents the reflectance in the red band.

NDVI values range from -1 to 1; values below 0 indicate non-vegetated areas (e.g., water or bare soil), while values between 0 and 1 represent vegetation, with values closer to 1 indicating healthier and denser vegetation. For nipah, the relevant NDVI range is 0.382-0.763 (AM et al. 2021). Elevation, slope, temperature, and rainfall data, also obtained from GEE, were used as supporting variables to extrapolate nipah's potential habitat based on the occurrence points. By combining nipah presence data with these relevant environmental variables through GEE, this study was able to accurately and efficiently map and predict the spread of nipah in the region, providing critical insights into the dynamics of this species' invasion within a degraded mangrove ecosystem.

RESULTS AND DISCUSSION

The time-series analysis of satellite data, using GEE from 2000 to 2024, reveals significant land cover change within the ATPF. The resulting maps identify six primary land cover types: nipah, open area, plantation, primary mangrove forest, secondary mangrove forest, and water body (Figure 2).

General overview of land cover changes (2000-2024)

At the beginning of the observation period in 2000, the ATPF ecosystem was largely dominated by mangrove forests (Figure 2). During this period, the ecosystem was unequivocally characterized by natural mangrove forests, with primary and secondary mangrove forests accounting for nearly 70% of the total area (Table 2). This high proportion underscored the pristine and extensive nature of the forest cover at the start of the study. However, the period up to 2024 saw a dramatic and concerning shift. By this period, the primary mangrove forest area had been halved, and the secondary mangrove forest was also substantially reduced. This collective loss of natural mangrove indicates significant fragmentation and conversion pressures on the core structure of the ecosystem. Concurrently, growth was explosive in both open areas and nipah coverage, particularly in the later period (2012-2024).

This substantially reduced mangrove coverage was counterbalanced by a sharp increase in other land cover types. Open areas experienced the fastest growth, expanding more than sixfold. Similarly, the nipah coverage increased by nearly five times its original size. Plantation areas exhibited fluctuations, characterized by an initial decrease between 2000 and 2012, followed by a dramatic increase from 2012 to 2024. This surge in land conversion during the last decade was primarily driven by the expansion of coconut and oil palm plantations, with the former being the more dominant land use in the area. This surge highlights intense anthropogenic pressure causing the degradation and conversion of the mangrove ecosystem into non-mangrove land.

Spatially, the maps from 2000 show primary mangrove forests widely distributed in the northern and western parts of the region. By 2024, however, the remaining primary and secondary mangrove forests were fragmented and concentrated mostly in the northern area. In contrast, plantations and open areas, which were initially more prevalent in the eastern and southern regions, had expanded northward by 2024.

Overall, the data points to a major ecological shift-from a dense, mangrove-dominated landscape to a more fragmented and anthropogenically influenced ecosystem, in which pioneer species such as nipah and open areas now occupy the largest segments of the total area. This change is further highlighted by the complete disappearance of the water-body category by 2024, possibly due to sedimentation or land conversion.

Analysis of the change rate of land cover

A detailed analysis of the change rates of land cover for the two periods (2000-2012 and 2012-2024) reveals an acceleration of the degradation process in the latter period (Figure 3). The decline in primary and secondary mangrove forest areas was significantly faster between 2012 and 2024. Primary mangrove forest coverage decreased by more than 20% during the last 12 years, a figure over four times greater than the loss recorded in the earlier period.

Conversely, the expansion of non-mangrove land covers, particularly nipah and open areas, accelerated sharply, signaling intensifying ecological pressure. The growth pattern of nipah coverage transformed dramatically between the two periods. Its initial expansion (2000-2012) was relatively modest, followed by an explosive surge in the later period (2012-2024). This surge suggests nipah's invasion potential was significantly enhanced in the most recent decade. Similarly, both open areas and plantations also recorded their most substantial increases in the latter period. This collective, rapid growth across non-mangrove categories-especially the shift from slow to high-speed expansion-provides clear evidence that nipah invasion and land conversion in this mangrove forest have reached a critical, fast-paced phase.

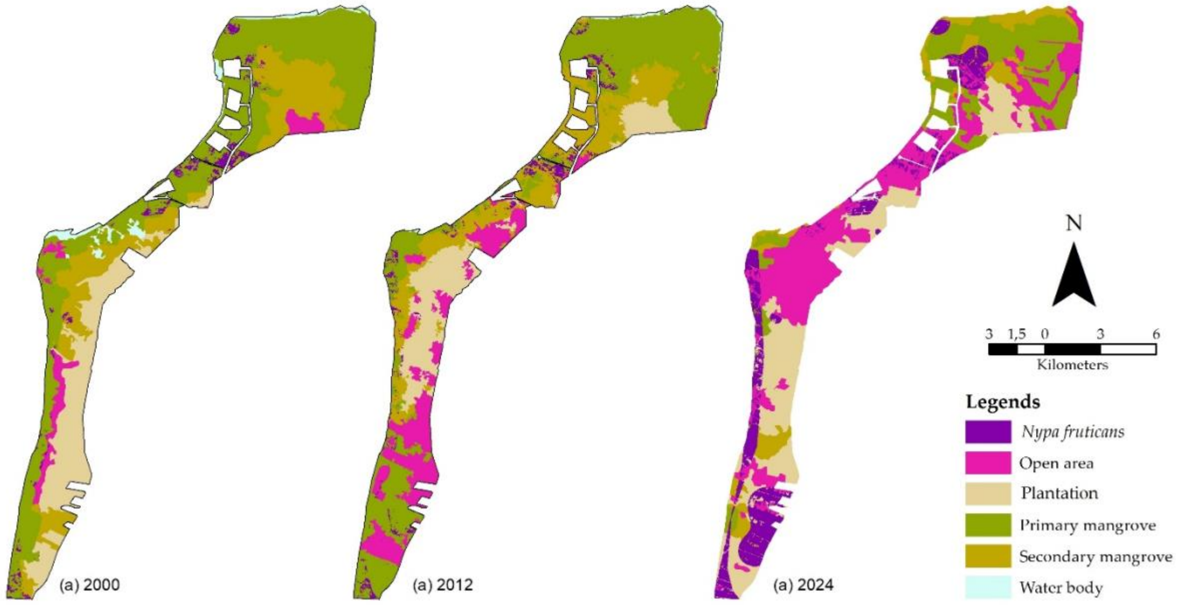

Figure 2. Map of land cover classification and distribution within the ATPF ecosystem in 2000, 2012, and 2024

Table 2. Area (ha) and percentage (%) of land cover types within the study site ecosystem over the observation period

Land cover type	Area in					
	2000		2012		2024	
	ha	%	ha	%	ha	%
Nypa	346.70	2.74	395.20	3.12	1,844.31	14.57
Open area	622.69	4.92	2,025.66	16.00	3,935.45	31.08
Plantation	2,472.72	19.53	2,021.71	15.97	3,039.01	24.00
Primary mangrove	5,840.77	46.13	5,260.74	41.55	2,644.74	20.89
Secondary mangrove	3,003.81	23.73	2,839.45	22.43	1,197.35	9.46
Water body	374.17	2.96	118.11	0.93	0.00	0.00
Total	12660.87	100.00	12660.87	100.00	12660.87	100.00

Note: ha: Area of land cover type in hectares; %: Percentage area of land cover type of the total ATPF area

Dynamics of nipah distribution

The mapping results specifically highlight the growth dynamics of the nipah population (Figure 4), showing a clear pattern of expansion in two distinct phases: (i) Initial growth (2000-2012): Nipah expansion during this period was relatively slow and modest, with an invasion rate of 4.04 ha/year. The increase in its coverage represented only a marginal proportion of the total area, suggesting an initial phase in which the species gradually established itself in limited, already disturbed niches within the ecosystem. (ii) Accelerated invasion (2012-2024): This later period witnessed a highly dramatic surge in nipah's growth, with the invasion rate skyrocketing to 120.76 ha/year. The area covered by nipah expanded exponentially, suggesting a transition into a rapid, aggressive invasion phase. This massive increase indicates that nipah quickly capitalized on the extensive land degradation and clearing that occurred, allowing it to dominate the newly available degraded lands and fundamentally alter the vegetation composition.

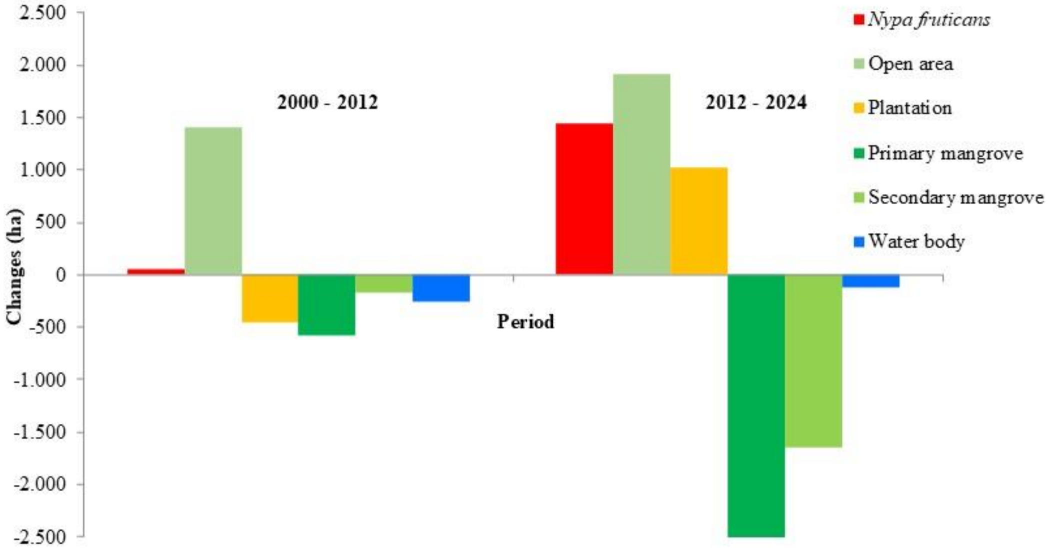

Figure 3. Comparative graph of the dynamics of land cover area across various types, highlighting changes between sub-periods

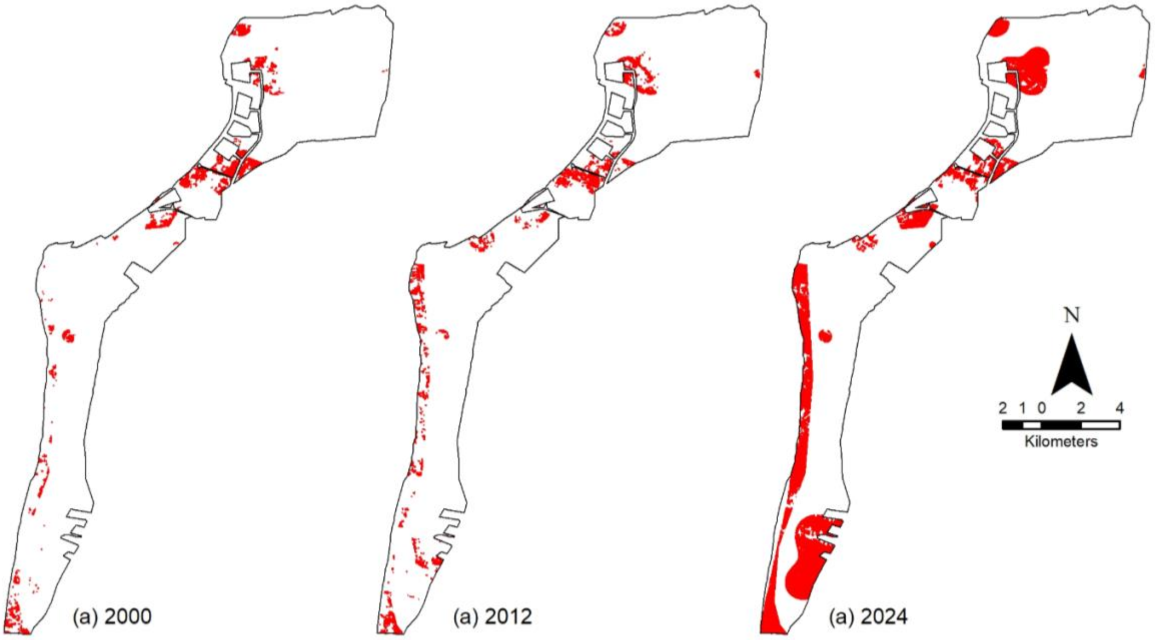

Figure 4. Spatial distribution map illustrating the dynamics of the nipah cover change within the ecosystem of the study site

Field analysis, supplemented by high-resolution aerial imagery captured using a drone, identified three categories of nipah density. Populations with low to medium density were found scattered across the southern and central zones of ATPF (Figures 5 and 6). In contrast, nipah with high density was heavily concentrated in the northern part (Figure 7).

This finding is supported by the invasive traits of nipah, which produces abundant seeds that are readily dispersed by water currents and can germinate in the muddy soils typical of degraded mangrove habitats (Figure 8). Its high reproductive capacity enables nipah to occur as scattered individuals or form dense colonies, depending on seed dispersal. Visual evidence shows heavy fruit clustering, widespread seeds on the ground, and seedlings establishing on both dry land and muddy substrates, indicating that mangrove degradation along coasts and riverbanks has created favorable conditions for rapid nipah expansion.

Discussion

Drivers of nipah invasion

The research methodology, which combined the strengths of GEE for large-scale time-series analysis with high-resolution imagery from drones, represents a state-of-the-art approach in ecological monitoring. GEE provides a powerful, planetary-scale platform for analyzing long-term trends in land cover changes, effectively overcoming the significant computational and data storage challenges typically associated with such analyses (Gorelick et al. 2017; Islam et al. 2025). This platform has proven its effectiveness in mapping changes in mangrove ecosystems globally (Yancho et al. 2020; Ghorbanian et al. 2021; Vu et al. 2022).

The integration of high-resolution drone imageries complemented the broad-scale analysis of GEE by providing detailed ground truth and fine-scale habitat characterization. This hybrid approach facilitated more accurate classification of land cover, including the critical differentiation of nipah population densities (Basyuni et al. 2023). This methodology is highly effective for monitoring invasive species and aligns with current trends in environmental remote sensing, which increasingly rely on multi-source data to monitor environmental changes and predict invasive species distribution (Farzanmanesh et al. 2024; Huang et al. 2024; Wang et al. 2025).

Figure 5. Areas with low densities of nipah population are found in the southern and central zones of the ATPF (nipah zones are marked with red circles), captured at a scale of 1:1,500 with an Unmanned Aerial Vehicle (UAV) altitude of 54 m

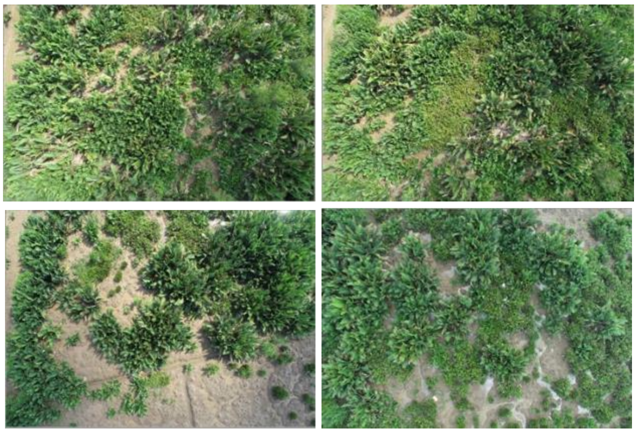

Figure 6. Areas with medium densities of nipah population are found in the southern and central zones of the ATPF, captured at a scale of 1:500 with an Unmanned Aerial Vehicle (UAV) altitude of 54 m

Figure 7. Areas with high densities of nipah population are found in the northern part of the ATPF, captured at a scale of 1:5,000 with an Unmanned Aerial Vehicle (UAV) altitude of 127.5 m

Figure 8. Nipah seedlings growing on muddy substrates, which are characteristic of the soil in mangrove forests

Our findings clearly link anthropogenic activities and the escalating degradation of the ATPF ecosystem, identifying these activities as the primary catalyst for nipah expansion. The dramatic reduction in the extent of primary and secondary mangrove forests directly correlates with the rapid increase in open areas and plantations. The transformation of dense mangrove forests into open areas within the ATPF is largely attributed to illegal logging and land occupation. Local communities clear these areas not only for timber extraction but also as a means to assert informal land ownership. Once the canopy is removed and the land is left as open areas, the ecological equilibrium is disrupted, providing an opportunistic window for nipah. As an aggressive pioneer species in disturbed habitats, nipah quickly colonizes these cleared sites, effectively hindering the recovery of primary and secondary mangrove species. This pattern is consistent with global research that pinpoints human activities, such as land conversion for agriculture and settlements, as major threats to mangrove health (Castillo et al. 2017a ; Eddy et al. 2021b).

A degraded ecosystem creates new ecological opportunities for pioneer species such as nipah. Removing native mangroves reduces competition and light limitation, creating ideal conditions for nipah colonization (Moudingo et al. 2020). The accelerated invasion rate observed in the second phase suggests that the ecosystem has crossed a critical threshold, allowing nipah to expand exponentially (Nwobi et al. 2020; Barenblitt et al. 2024). The distinct spatial patterns of nipah density-high in the north and low in the south-further underscore this point. The massive land clearing in the northern region and the government's port development project at Tanjung Carat created extensive disturbed, open areas highly susceptible to invasion. Conversely, the southern part of the ATPF, which has been managed as a coconut plantation by the community since the 1970s, is regularly maintained, suppressing nipah's ability to establish large, dense colonies.

The invasion of nipah is not confined to inland areas. The tendency of nipah to grow in the central to southern regions of the ATPF is also observed along the banks of the Banyuasin River (west region). This area shows significant degradation, with sparse native mangrove populations replaced by nipah. The presence of nipah along the river's edge strongly indicates massive mangrove forest degradation. Nipah, as an opportunistic species, can quickly colonize disturbed areas, taking advantage of the absent competition from native vegetation (Widodo et al. 2020). This phenomenon confirms the degradation not only in inland areas but also in the coastal zones directly bordering major waterways, ultimately broadening the scope of the nipah invasion.

Land cover trajectory

Based on the observed trends in land cover changes from 2000 to 2024, a clear future trajectory for the ATPF can be projected. The continuous decline of primary and secondary mangrove forests, coupled with the accelerated expansion of nipah colonies, open areas, and plantations, points to a future in which the integrity of the ecosystem is severely compromised. If these trends persist, primary and secondary mangrove forests will probably be completely eliminated from the region within the next few decades. This possibility aligns with studies showing that unchecked human disturbance and land conversion can complete the disappearance of mangrove ecosystems (Castillo et al. 2017b). Consequently, the area occupied by nipah colonies, open areas, and plantations is projected to continue its exponential growth, potentially dominating the entire landscape. This shift will establish a homogenous vegetation dominated by nipah, a scenario documented in other invaded ecosystems in which native species are unable to compete (Numbere and Moudingo 2023; Liu et al. 2024). The complete loss of native mangrove forests would represent an irreversible ecological collapse, with severe implications for biodiversity, carbon sequestration capacity, and overall resilience of this ecosystem (Chowdhury et al. 2023; Eddy et al. 2024a).

The future trajectory presented in this study is a projection rather than a certainty, as it assumes that the current human-induced effects will continue unabated. However, this outlook could be positively altered by future conservation interventions. For instance, the successful implementation of the National Mangrove Restoration Program or stricter enforcement of land-use regulations could slow or even reverse the projected decline of native mangroves. As highlighted by Budiharta and Holl (2025), upscaling such restoration efforts in Indonesia can be effectively achieved by harnessing opportunities in social forestry and ecosystem restoration concessions, which align funding with local benefits. Similarly, the scaling up of community-based management and the development of sustainable nipah-based economies could provide economic incentives to manage and control the invasive species actively. The long-term fate of the region, therefore, depends on the effectiveness of future policy interventions and the level of community engagement in integrated restoration strategies.

Comparison with other global regions

The accelerated nipah expansion in the ATPF ecosystem mirrors the devastating pattern documented in other regions such as West and Central Africa, highlighting a global concern regarding this invasive species (Moudingo et al. 2020; Numbere and Moudingo 2023). While nipah is native to Southeast Asia, its rapid proliferation in areas such as the Niger Delta is linked to anthropogenic disturbances such as rapid mangrove forest loss and land conversion (Numbere 2019a; Nwobi et al. 2020). Critically, the pace of invasion in ATPF-shifting from modest growth to an explosive surge in the later period-suggests that, as in African scenarios, the ecosystem has crossed a threshold at which degradation has created optimal, low-competition conditions for nipah to aggressively outcompete native mangroves, potentially changing forest structure permanently (Numbere 2019b). This rapid dominance by nipah in degraded areas, as also seen locally in regions such as Cilacap (Widodo et al. 2020), underscores the need for urgent management strategies to prevent nipah from completely replacing the primary mangrove structure-a common outcome in critically invaded coastal areas worldwide.

Ecological implications and management strategy

The invasion of nipah in ATPF presents a significant threat with far-reaching impacts on ecological, economic, social, and global climate systems. The extensive spread of nipah reduces native mangrove biodiversity by outcompeting indigenous species (Barenblitt et al. 2024). This homogenous vegetation alters habitat structure and negatively impacts faunal diversity, including macrozoobenthos and avifauna, which depend on a healthy and diverse mangrove ecosystem (Basyuni et al. 2018; Eddy et al. 2021c).

Nipah invasion has severe implications for the ecosystem's role as a carbon sink. Our studies have demonstrated that mangrove degradation due to human activities results in a significant loss of carbon stocks and the release of carbon emissions (Eddy et al. 2021a; 2023a). While nipah does store carbon, the capacity of nipah is generally lower than that of dense primary and secondary mangrove forests (Basyuni et al. 2021). The replacement of native mangroves with nipah reduces the overall carbon storage potential of the ATPF, thus contributing to increased greenhouse gas emissions and global warming, consistent with global reports on biodiversity loss and climate change (Almond et al. 2020; Cooley et al. 2022).

The complete loss of native mangrove forests would represent an irreversible ecological collapse, with severe implications for biodiversity, carbon sequestration capacity, and overall resilience of this ecosystem (Chowdhury et al. 2023; Eddy et al. 2024a). As native mangroves are replaced, the overall carbon storage capacity of the area is diminished, directly contributing to greenhouse gas emissions and compromising Indonesia's climate change mitigation commitments (Eddy et al. 2023a).

Uncontrolled nipah invasion disrupts vital ecosystem services. It compromises the ability of the mangrove forest to protect the coast from natural disasters such as storm surges (Ouyang et al. 2018; Hochard et al. 2019) and diminishes fish habitats, directly affecting the livelihoods of coastal communities. The resulting change in resource availability can also promote social conflicts (Mai et al. 2019; Gallardo et al. 2024). This scenario clearly exemplifies how unchecked land conversion can create a cascading ecological failure, compromising climate mitigation goals and marine biodiversity (Eddy et al. 2021a; Alongi 2022).

Effectively addressing the nipah invasion requires a collaborative and integrated approach involving communities, government, and academia. Empowering local communities through education on the impacts of the invasion and training on the sustainable use of nipah is crucial. Developing value-added economic products from nipah, such as sugar, vinegar, or bioenergy, can financially incentivize communities to manage the nipah population sustainably (Panyadee et al. 2022; Wijana et al. 2023; Eddy et al. 2023b). By balancing conservation with local livelihood needs, this approach aligns with sustainable development goals (Sasmito et al. 2023).

Government policy must enforce existing regulations against illegal logging and land conversion while restoring degraded mangrove areas with native species. Restoration efforts should focus not just on replanting but also on restoring the hydrological and soil conditions that support the growth of native mangroves (Castillo et al. 2017b; Basyuni et al. 2021; Eddy et al. 2023a). Integrating nipah management into ecotourism programs can transform the invasive species into a unique attraction, creating a sustainable economic model (Rahman et al. 2024). Research into the potential of nipah for producing high-value products, such as vegetable oil, can provide new avenues for sustainable exploitation (Eddy et al. 2025).

Furthermore, our findings provide a vital empirical contribution to contemporary literature on mangrove conservation, which increasingly focuses on the complex interplay of human pressures, climate change, and ecosystem resilience. Recent studies emphasize that effective mangrove conservation must progress beyond traditional protection and restoration efforts, addressing systemic issues such as land use policy, community engagement, and the management of multiple stressors (Sasmito et al. 2023). By integrating our findings with these global frameworks, we offer a valuable model that demonstrates how a successful conservation strategy must holistically address both the invasive species and the underlying drivers of ecosystem degradation.

The results of this research carry significant implications for both national conservation strategies and global sustainability goals. The proliferation of nipah seriously threatens the ecosystem's biodiversity, carbon storage, and overall resilience (Chowdhury et al. 2023; Eddy et al. 2024a). As native mangroves are replaced, the overall carbon storage capacity of the area is diminished, directly contributing to greenhouse gas emissions and compromising Indonesia's climate change mitigation commitments (Eddy et al. 2023a). Effectively addressing this problem requires a multifaceted strategy that moves beyond simple tree-planting initiatives. A successful approach must involve stricter enforcement against land conversion, large-scale ecological restoration, and the empowerment of local communities through sustainable economic uses of nipah (Sasmito et al. 2023; Wijana et al. 2023). Integrating advanced monitoring with robust policy and community engagement can restore the ecological integrity of the ATPF and align its management with the National Mangrove Restoration Program and key Sustainable Development Goals (SDGs), specifically SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

For the ATPF, the future trajectory presented in this study, while grounded in observed historical trends, is a projection rather than a certainty. The trajectory assumes that the current human-induced effects will continue unabated. However, this outlook could be positively altered by future conservation interventions. For instance, the successful implementation of the National Mangrove Restoration Program or stricter enforcement of land-use regulations could slow or even reverse the projected decline of native mangroves. Similarly, the scaling up of community-based management and the development of sustainable nipah-based economies could provide economic incentives to manage and control the invasive species actively. The long-term fate of the region, therefore, depends on the effectiveness of future policy interventions and the level of community engagement.

Despite these insights, this study has several limitations. Some environmental variables used in modeling, such as rainfall and soil data, were only available at coarse spatial resolutions, which may obscure micro-scale habitat differences relevant to nipah distribution. Minor misclassification remains possible in the historical satellite time series due to spectral similarity among land cover types, the challenges in fully controlling seasonal variation, and potential cloud contamination in older Landsat scenes. Crucially, the lack of in situ vegetation structure measurements for the 2000 and 2012 time points limited our ability to fully validate early forest characteristics. Additionally, the long intervals between temporal data points limit the ability to capture short-term fluctuations or episodic disturbances that may influence invasion dynamics.

Future research should incorporate higher-resolution environmental datasets, systematic field validation, and hydrological assessments to better understand the drivers facilitating nipah establishment, while also employing multi-temporal analysis-as demonstrated by Feng et al. (2022)-to quantify the specific land-cover transitions and identify areas most vulnerable to nipah replacement. Scenario-based modelling-such as simulations under alternative land-use regulations or restoration interventions-would also strengthen predictions of future ecosystem trajectories. Integrated restoration, enforcement, and community stewardship are urgently required.

In conclusion, the results of this study show that extensive human-driven degradation has severely reduced native mangrove cover in the Air Telang Protected Forest (ATPF), creating the ecological conditions that enabled a rapid and large-scale invasion of *N. fruticans* over the past two decades. The accelerated expansion of nipah between 2012 and 2024 indicates that the ecosystem has likely crossed disturbance threshold that favors nipah dominance, with substantial implications for biodiversity loss, reduced carbon storage, and long-term ecosystem instability. The hybrid approach-combining GEE-based time-series mapping with high-resolution drone validation-provides strong evidence that nipah proliferation is tightly linked to anthropogenic land conversion, habitat fragmentation, and the decline of primary and secondary mangrove stands. As nipah replaces native mangroves, the structural and functional integrity of the ecosystem is diminished, threatening habitat quality, carbon sequestration capacity, and coastal resilience.

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