Environment and Natural Resources Journal

Volume 24
Issue 4
2026

Land Use and Land Cover Dynamics of Small Inhabited Islands in South Bangka, Bangka Belitung, Indonesia (2004-2024)

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ARTICLE INFO

Received: 22 Nov 2025
Received in revised: 13 Jan 2026
Accepted: 18 Feb 2026
Published online: 30 Apr 2026
DOI: 10.32526/ennrj/24/20250333

Keywords:
Ecosystem conservation/ Landscape connectivity/ LULC change/ Remote sensing/ Small islands

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ABSTRACT

Anthropogenic land use and cover changes pose a significant threat to small island ecosystems, yet systematic monitoring remains limited. This study analyzes LULC dynamics over 20 years (2004-2024) on three inhabited islands in South Bangka, Bangka Belitung, Indonesia. The objectives were to assess LULC changes, evaluate their impacts on biodiversity, and examine the effectiveness of existing policies using multi-temporal Landsat and Sentinel-2 imagery. The supervised classification achieved an overall accuracy of 85.3-91.2% with Kappa coefficients of 0.82-0.89, indicating substantial to nearly perfect agreement. The results revealed distinct transformation patterns across the islands. Tinggi Island demonstrated resilience through the recovery of secondary dryland forests (from 68.52 ha to 113.48 ha), despite the presence of illegal tin mining activities that created artificial wetland systems. In contrast, Kelapan Island faced severe degradation, with extensive forest loss and habitat fragmentation. This resulted in a 29.5% decline in mean patch size and a critical loss of connectivity. Conversely, Pongok Island showcased successful conservation efforts, significantly expanding its mangrove ecosystem, which enhanced its blue carbon capacity, even amid agricultural intensification. The assessment of biodiversity impacts confirmed that maintaining patch sizes above 20 hectares and ensuring high connectivity are essential thresholds for species conservation. However, current LULC management policies demonstrate limited effectiveness due to regulatory gaps between marine and terrestrial governance frameworks. The study concludes that integrated conservation strategies, including adaptive management and corridor restoration, are urgently needed to balance development pressures with the preservation of ecosystem integrity.

HIGHLIGHTS

- Multi-temporal Landsat-Sentinel fusion analyzed 20-year LULC dynamics.
- Supervised classification achieved 85-91% accuracy with Kappa 0.82-0.89.
- Three islands showed distinct patterns: recovery, degradation, and conservation.
- Patch size >20 ha and high connectivity are critical for species survival.
- Marine-terrestrial governance gaps limit conservation policy effectiveness.

1. INTRODUCTION

Anthropogenic transformations in land use and land cover (LULC) are significant drivers of global environmental change, adversely affecting ecosystem integrity, biodiversity, and human well-being (Baidoo et al., 2023; Kusiima et al., 2022; Smith et al., 2019). These changes have accelerated in recent decades due to population growth, economic development, and technological advancements, placing unprecedented pressure on terrestrial ecosystems (Rachman et al., 2024; Zhang et al., 2025a). Since 1960, global land conversion has increased by 50%, with Small Island Developing States (SIDS) experiencing even higher rates due to limited land and intense development pressures (UNEP, 2023).

Citation: Henri, Hakim L, Retnaningdyah C, Rahardi B. Land use and land cover dynamics of small inhabited Islands in South Bangka, Bangka Belitung, Indonesia (2004-2024). Environ. Nat. Resour. J. 2026;24(4):422-434. (https://doi.org/10.32526/ennrj/24/20250333)

Small islands (≤2,000 km²) are particularly vulnerable, hosting 15-20% of terrestrial species despite occupying only 5.5% of Earth's land (Kueffer and Kinney, 2017; Médail, 2017). Land use changes in small islands occur 2-3 times faster than in continental regions, with over 40% of tropical small islands losing more than 10% of their natural cover each decade (Ahmed et al., 2023; Chen et al., 2023). These changes involve complex interactions between proximate causes and underlying drivers (Sisay et al., 2024).

Recent advancements in remote sensing and Geographic Information Systems (GIS) have significantly improved our capacity to monitor LULC dynamics, particularly in remote areas where ground surveys are challenging (Faruque et al., 2022; Singh et al., 2020). Since 1972, the continuous flow of satellite imagery from sources like Landsat has enabled long-term detection and analysis of changes in land cover (Masek et al., 2020). The 30-meter resolution and consistent temporal coverage of the Landsat archive are invaluable for monitoring small islands, where even minor changes have significant ecological impacts (Hemati et al., 2021; Radeloff et al., 2024).

Comprehensive monitoring is essential in small island environments, where geographic isolation and limited resources amplify the impacts of land use changes (Kelman, 2018; Setiawati et al., 2023). Examples include Saint Martin Island in Bangladesh, where built-up areas increased from 2.97% to 21.42% between 2005 and 2021 (Ahmed et al., 2023), and Belitung Island in Indonesia, which experienced a greater than 25% decrease in forest cover from 1990 to 2020 (Oktavia et al., 2024).

South Bangka, part of the Bangka Belitung Island Province, encompasses numerous small inhabited islands that illustrate the complex dynamics of LULC characteristic of Indonesian archipelagos. These islands are home to traditional fishing and subsistence agriculture communities (Achmad et al., 2022; Pical and Rahman, 2025). Economic diversification and developmental pressures reshape these livelihoods, leading to mixed strategies incorporating seaweed cultivation and small-scale tourism (Reksa et al., 2021; Rimmer et al., 2021).

Despite their significance, small inhabited islands frequently lack systematic, long-term monitoring of LULC dynamics (Révillion et al., 2019). Most research concentrates on larger regions, resulting in significant knowledge gaps regarding LULC changes on individual small islands (Purnama and Çoban, 2024). This shortfall limits our understanding of landscape evolution and the underlying factors driving these changes (Li et al., 2023). Enhanced monitoring and detailed LULC mapping are crucial for assisting policymakers in balancing economic development with environmental conservation (Duan et al., 2025; Yetein et al., 2025).

This study presents a comprehensive 20-year analysis (2004-2024) of LULC dynamics on small inhabited islands in South Bangka, utilizing multi-temporal Landsat imagery and GIS techniques. The objectives are to (1) assess the changes in LULC on small inhabited islands from 2004 to 2024, (2) evaluate the impacts of these LULC changes on biodiversity, and (3) evaluate the effectiveness of LULC management policies in small islands.

2. METHODOLOGY

2.1 Study area and data acquisition

This study focused on three small inhabited islands located in South Bangka, Bangka Belitung Province, Indonesia: Kelapan Island, Pongok Island, and Tinggi Island (2°30'S-3°00'S, 106°30'E-107°00'E) (Figure 1).

We utilized multi-temporal satellite imagery from three significant periods: Landsat 7 ETM+ (2004), Landsat 7 ETM+ with high-resolution correction (2014), and Sentinel-2 L2A (2024). All images were captured during the dry season with less than 10% cloud cover to ensure optimal quality. This timeline corresponds with key policy milestones: 2004 serves as the baseline prior to the implementation of formal spatial planning policies; 2014 reflects the period after the South Bangka Regency Spatial Plan was enacted, allowing for a midpoint evaluation; and 2024 provides the most recent observations for assessing long-term effectiveness. The 10-year intervals are effective for identifying significant land-use and land-cover changes, as major transformations tend to unfold over time (Gómez et al., 2016). Cross-sensor radiometric calibration was performed to ensure spectral alignment between the Landsat 7 ETM+ and Sentinel-2 sensors.

Although a higher temporal resolution could capture inter-annual variations, persistent tropical cloud cover and the necessity for consistent dry-season imagery constrained data availability. To supplement our analysis, we incorporated historical land cover maps from the Indonesian Ministry of Environment and Forestry (KLHK) along with local government planning documents for additional

context. Administrative boundary maps were sourced from the Geospatial Information Agency (BIG), and GPS technology was employed for ground-truth data collection during field surveys in 2024 to validate the accuracy of our classifications.

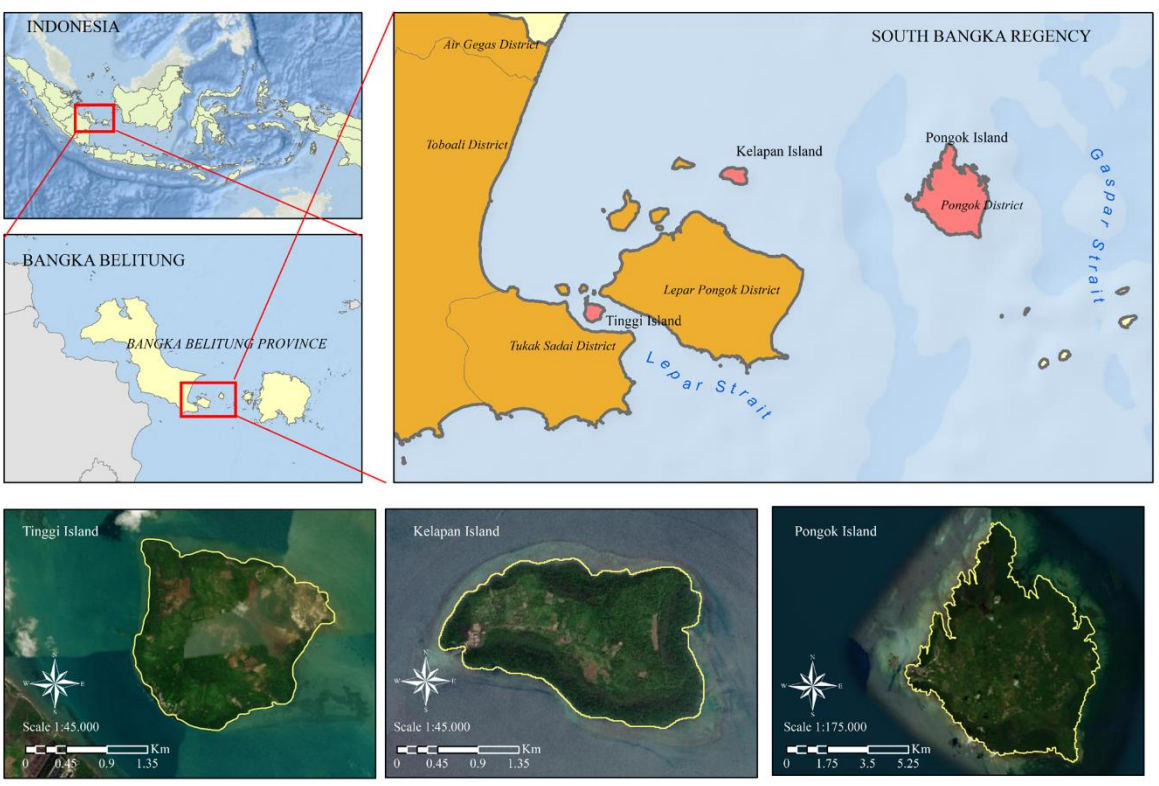

Figure 1. Study the area of LULC on small inhabited islands in South Bangka, Bangka Belitung

2.2 Image processing and classification

Atmospheric correction for Landsat 7 ETM+ imagery was carried out using the Dark Object Subtraction (DOS) method to derive surface reflectance (Shrestha et al., 2019). Sentinel-2 Level 2A data underwent correction using advanced quality-enhancing algorithms. Geometric correction achieved a root mean square error (RMSE) of less than 0.5 pixels, which is essential for accurate quantitative analyses. Furthermore, cross-sensor calibration utilizing pseudo-invariant features helped reduce inter-sensor biases (Khakurel et al., 2021).

Two classification schemes were developed: the Ministry of Environment and Forestry (KLHK) method, which consists of nine categories, and the Intergovernmental Panel on Climate Change (IPCC) framework, comprising six categories. In the IPCC-KLHK crosswalk, 'Wet Shrubland' was classified as 'Grassland' due to similarities in vegetation height, canopy cover, and aboveground carbon stocks (Kauffman et al., 2020). Supervised classification was performed using the Maximum Likelihood Classifier (MLC) within QGIS 3.28, with training samples collected through stratified random sampling, ensuring a minimum of 50 pixels per class (Congalton and Green, 2019). The spectral separability of class pairs was validated using the Jeffries-Matusita distance, with all pairs exceeding the 1.9 threshold (Legleiter et al., 2016).

Mangrove vegetation was hierarchically classified into primary and secondary types based on canopy density. Primary mangroves, characterized by continuous forest cover from 2004 to 2024, exhibited NDVI values ≥ 0.43 and high texture heterogeneity (GLCM entropy > 4.0). Conversely, secondary mangroves exhibited signs of historical disturbances, characterized by lower NDVI values (0.33-0.42) and a more uniform canopy texture (Pham et al., 2019). Canopy density classifications included dense (NDVI ≥ 0.43), moderate ($0.33 \leq$ NDVI < 0.43), and sparse (NDVI < 0.33) (Faizal et al., 2025). Accuracy was validated using 180 reference points from field surveys conducted in 2024, complementing high-resolution imagery. This was followed by majority filtering and manual editing to minimize noise and correct errors (Phiri and Morgenroth, 2017).

2.3 Accuracy assessment and change detection

The classification accuracy was assessed using 300 stratified random reference points for each island and each time period. This was validated against 2024 field GPS data (n=150 points) and visual interpretation of high-resolution satellite imagery from Google Earth Pro for historical periods. Reference points were allocated proportionally based on class area, following standard remote sensing protocols. The accuracy metrics included overall accuracy (OA), producer's accuracy (PA), user's accuracy (UA), and the Kappa coefficient. The results indicated an overall accuracy ranging from 85.3% to 91.2% across different islands and time periods, with Kappa values between 0.82 and 0.89, signifying substantial to nearly perfect agreement. Most categories showed per-class accuracies exceeding 80%, with mangrove and settlement classes achieving the highest accuracies of over 90%. In contrast, mixed agriculture displayed lower accuracy (75-82%) due to its spectral similarity with shrubland. The accuracy assessment adhered to the protocols outlined, resulting in a minimum overall accuracy of 85%, complemented by Kappa coefficient calculations. Geometric correction achieved RMSE values of 0.42 pixels (Landsat 2004), 0.38 pixels (Landsat 2014), and 0.35 pixels (Sentinel-2 2024), all of which are below the 0.5-pixel threshold required for accurate quantitative analyses. According to Landis and Koch (1977), interpretation guidelines, the Kappa values of 0.82-0.89 indicate 'substantial to almost perfect agreement', confirming the statistical reliability and significance of the classification results (Desjardins et al., 2023).

Using the post-classification comparison technique in QGIS, a quantitative analysis of the geographical and temporal dynamics of LULC was conducted, producing change matrices for 2004-2024. A comprehensive analysis of forest-to-other land use conversion rates was performed to examine patterns of forest degradation. Forest degradation rates were calculated using the compound interest formula (Puyravaud, 2003): $r=(1/t) \times \ln(A_2/A_1) \times 100$, where r is the annual change rate (%), A_1 and A_2 are initial and final forest areas (ha), and t is the time interval (years). Landscape metrics were computed using FRAGSTATS 4.2 (McGarigal et al., 2012): number of patches (NP), mean patch size (MPS=A/NP), edge density (ED=E/A × 10,000), Shannon diversity index ($SHDI=-\Sigma(p_i \times \ln p_i)$), and most extensive patch index ($LPI=\max(a_i)/A \times 100$). Forest connectivity was assessed based on combined MPS and ED values.

2.4 Data analysis

Land use and land cover (LULC) changes from 2004 to 2024 were analysed using descriptive statistics, including area, percentage change, and annual rates. Landscape fragmentation metrics were compared to ecological thresholds for biodiversity conservation. Given the limited data collection (three time points), the focus was on the significance of the observed changes. Data processing was conducted in QGIS and Excel. Limitations included cloud cover, mixed pixel effects, and seasonal fluctuations in vegetation.

3. RESULTS AND DISCUSSION

3.1 LULC change patterns and forest resilience

Over the past two decades, changes in land use and land cover (LULC) on the small islands of Bangka Belitung Province have showcased diverse ecosystem dynamics, illustrating the interplay between natural regeneration and human influences. These patterns provide valuable insights into the adaptive capacity of tropical coastal ecosystems, highlighting the impact of local management practices, the distinct characteristics of ecosystems, and the delicate balance between disturbance intensity and regeneration processes.

Tinggi Island exemplifies recovery in secondary dryland forest ecosystems, showcasing 15.05 hectares of regeneration after a decline from 2004 to 2014 (see Table 1 and Figure 2). This reflects ecological succession theory, which suggests that reduced disturbances aid vegetation restoration. Studies indicate that natural regeneration often results in greater biodiversity than active restoration (Crouzeilles et al., 2017). Effective forest management strategies on the island, such as preserving residual forest patches, can enhance recovery by providing seed sources (Zhang et al., 2025b). Moderate fragmentation levels may also support this process, encouraging colonisation by locally adapted species and fostering a diverse ecosystem (Crouzeilles et al., 2017). Additionally, research by Mukul et al. (2020) notes that initial rapid recovery can lead to changes in tree density as the forest matures, highlighting dynamic growth patterns in Tinggi Island's secondary forests.

Table 1. Changes to the LULC classification of Tinggi Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	19.32	6.12	19.84	6.27	26.60	8.41	+7.28	+2.29
Forest land	Primary mangrove forest	59.80	18.93	61.27	19.37	67.49	21.33	+7.69	+2.40
	Secondary dryland forest	98.43	31.16	68.52	21.66	113.48	35.86	+15.05	+4.70
	Secondary mangrove forest	11.61	3.68	12.12	3.83	7.13	2.25	-4.48	-1.42
Grassland	Wet shrubland	93.37	29.56	79.04	24.99	52.34	16.54	-41.03	-13.02
Other land	Bare ground	28.23	8.94	63.52	20.08	18.55	5.86	-9.68	-3.07
Settlement areas	Settlement areas	1.26	0.40	2.14	0.68	2.54	0.80	+1.28	+0.40
Wetland	Swamp	3.75	1.19	7.66	2.42	25.20	7.96	+21.45	+6.78
	Water bodies	0.07	0.02	2.18	0.69	3.10	0.98	+3.03	+0.96
Total area (ha)		315.84		316.28		316.43			

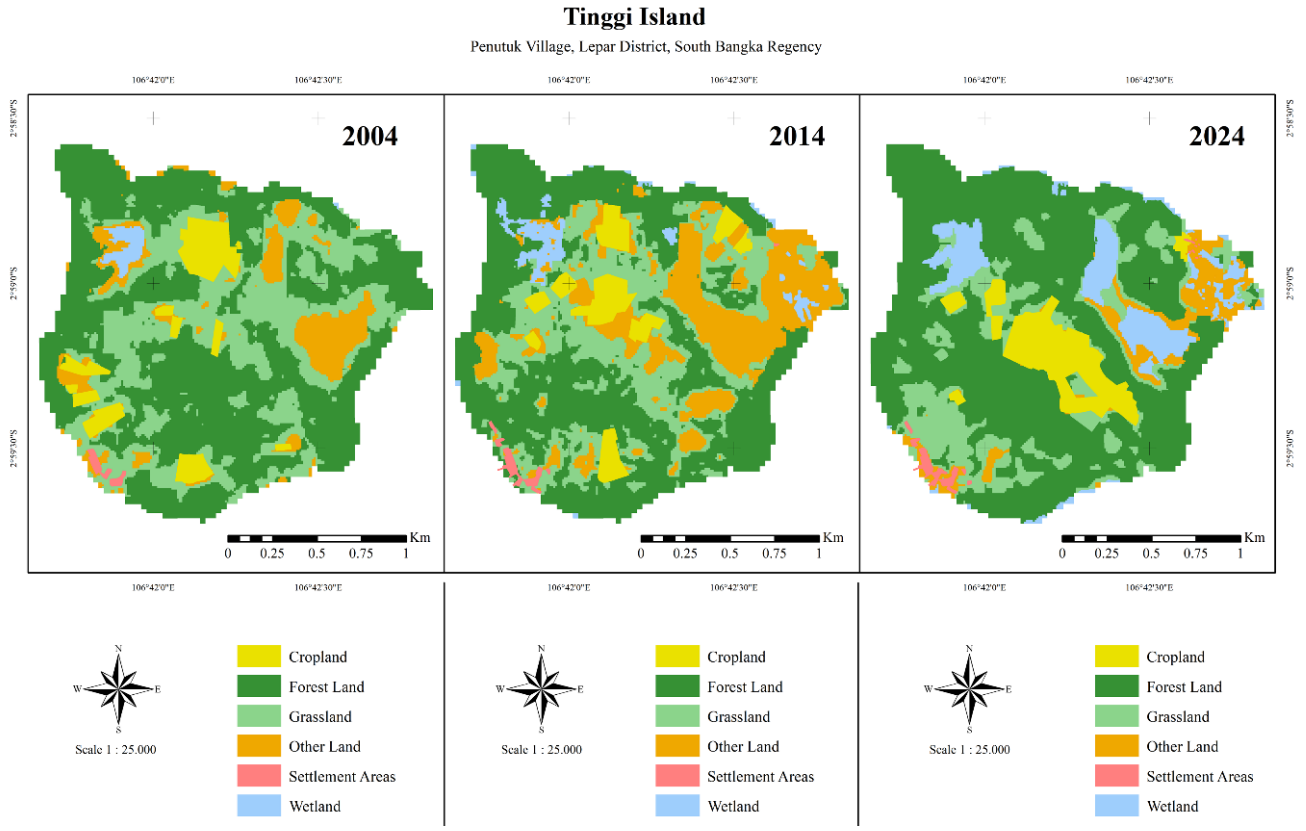

Figure 2. LULC changes in Tinggi Island for the years 2004, 2014, and 2024

The 2.40% increase in primary mangrove forests, alongside the preservation of dryland forests, indicates that conservation efforts are yielding positive results (Table 1 and Figure 2). Mangroves play a vital role as ecosystem engineers, demonstrating significant responsiveness to protective measures. This reinforces the idea that well-implemented conservation strategies can deliver considerable benefits for biodiversity and ecosystem functionality in tropical coastal regions. The increase in wetland areas from 3.75 to 25.20 hectares signifies the conversion of bare ground into wetland, primarily driven by illegal artisanal tin mining activities, locally referred to as 'tambang inkonvensional' or TI. These mining operations create excavated pits that eventually fill with water, resulting in artificial wetland systems known as 'kolong'. The hydrological disruption caused by mining alters natural drainage patterns, leading to water accumulation in former bare mining sites. Over time, these water-filled pits acquire characteristics of

wetland vegetation through the process of natural succession. This transformation raises significant concerns regarding the integrity of the habitat. Research indicates that while secondary forests can regenerate, ongoing human pressures may substantially modify ecosystem composition and structure (Li et al., 2024).

Furthermore, understanding biodiversity recovery in secondary forests requires an examination of the complex interactions among multi-trophic species, especially in fragmented landscapes (Timmers et al., 2025). The interplay between forest recovery and human disturbance on Tinggi Island demonstrates that while natural regeneration can occur, sustained external pressures may hinder this process, necessitating integrated management approaches (Li et al., 2024). Kelapan Island has recently experienced significant ecological disturbances, resulting in a net loss of 46.06 hectares of secondary dryland forest, which represents 12.02% of its area as established in the 2004 baseline (Table 2 and Figure 3). This degradation level suggests that forest clearing rates have exceeded natural regeneration capacity, potentially approaching ecological tipping points beyond which recovery may be compromised (Obura et al., 2023).

Table 2. Changes to the LULC classification of Kelapan Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	10.07	2.62	7.47	1.94	8.40	2.18	-1.67	-0.44
Forest land	Primary mangrove forest	67.98	17.69	71.58	18.62	74.27	19.30	+6.28	+1.62
	Secondary dryland forest	184.82	48.08	100.89	26.25	138.77	36.07	-46.06	-12.02
	Secondary mangrove forest	21.33	5.55	26.51	6.90	22.99	5.97	+1.66	+0.43
Grassland	Wet shrubland	71.28	18.54	137.97	35.89	118.70	30.85	+47.43	+12.31
Other land	Bare ground	23.30	6.06	36.30	9.44	12.94	3.36	-10.36	-2.70
Settlement areas	Settlement areas	1.52	0.39	1.89	0.49	2.29	0.60	+0.78	+0.20
Wetland	Swamp	4.08	1.06	1.28	0.33	0.68	0.18	-3.40	-0.88
	Water bodies	0.00	0.00	0.47	0.12	5.71	1.48	+5.71	+1.48
Total area (ha)		384.38		384.36		384.74			

Land clearing for agriculture, particularly for clove plantations and selective logging, has led to habitat fragmentation, isolating remaining environmental patches and reducing ecosystem resilience (Hazwan et al., 2022). While primary mangrove forests have expanded by 6.28 hectares (Table 2 and Figure 3), this increase is insufficient to compensate for dryland forest degradation. Research confirms that such ecological disruptions negatively impact biodiversity and ecosystem functioning, highlighting the connection between habitat loss and environmental integrity (Gunawan et al., 2024a).

The 47.43-hectare (12.31%) increase in wet shrubland on Kelapan Island reflects a transitional phase in its ecological trajectory (Table 2 and Figure 3), consistent with the principles of ecological succession theory. Following forest clearing, pioneer species colonize disturbed areas, leading to simplified vegetation structure. This transition may reduce the island's ecological resilience and warrants conservation attention (Tripathi et al., 2020). Human-induced changes pose significant threats to ecosystem functionality and species interactions (Carugati et al., 2018).

Pongok Island stands out as a remarkable example of effective mangrove conservation, having recorded an increase of approximately 275.76 hectares, or 5.82%, in its primary mangrove forests (Table 3 and Figure 4). This growth highlights the success of restoration efforts and habitat protection initiatives. Primary mangrove forests are vital for providing essential ecosystem services, such as carbon sequestration, serving as nursery habitats for marine life, and offering protection to coastal areas (Miller and Tonoto, 2023). They have the capacity to sequester significantly more carbon than tropical terrestrial forests, highlighting their crucial role in biodiversity conservation and climate change mitigation through blue carbon storage (Alongi, 2020; Taillardat et al., 2018).

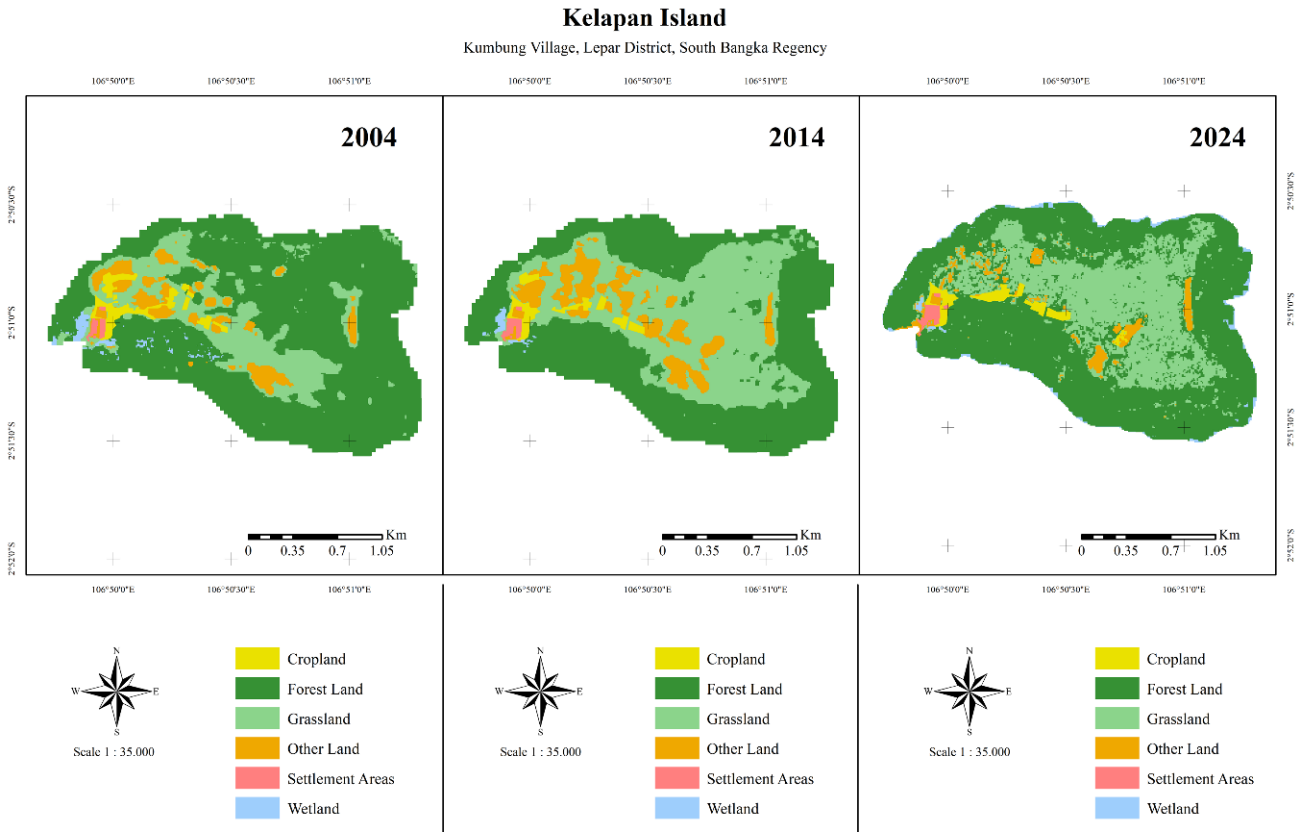

Figure 3. LULC changes in Kelapan Island for the years 2004, 2014, and 2024

Table 3. Changes to the LULC classification of Pongok Island from 2004 to 2024

LULC Class		2004		2014		2024		Change 2004-2024	
IPCC	KLHK	Ha	%	Ha	%	Ha	%	Ha	%
Cropland	Mixed dry agriculture	6.39	0.13	14.30	0.30	178.84	3.72	+172.45	+3.59
Forest land	Primary mangrove forest	1,436.74	29.81	1,671.71	34.66	1,712.50	35.64	+275.76	+5.82
	Secondary dryland forest	183.86	3.82	119.43	2.48	220.75	4.59	+36.89	+0.78
	Secondary mangrove forest	62.94	1.31	55.00	1.14	4.26	0.09	-58.68	-1.22
Grassland	Wet shrubland	2,477.78	51.42	2,168.23	44.96	1,923.89	40.04	-553.90	-11.38
Other land	Bare ground	588.57	12.21	663.82	13.77	660.15	13.74	+71.58	+1.52
Settlement areas	Settlement areas	36.51	0.76	42.88	0.89	43.33	0.90	+6.82	+0.14
Wetland	Swamp	9.41	0.20	41.64	0.86	14.16	0.29	+4.75	+0.10
	Water bodies	16.66	0.35	45.48	0.94	47.19	0.98	+30.53	+0.64
Total area (ha)		4,818.86		4,822.49		4,805.06			

Pongok Island has faced a notable decline in its secondary mangrove forests, with approximately 58.68 hectares, or 93.23%, lost. Although secondary mangroves hold less ecological value compared to primary forests, they remain essential for creating habitats and facilitating ecosystem recovery (Eddy et al., 2021). This reduction can be attributed to both natural processes and human activities, particularly illegal tin mining, which disrupts the ecological balance (Pratiwi et al., 2025). The concurrent 172.45-hectare expansion of mixed dry agriculture reflects increasing economic pressures that must be balanced with conservation priorities (Musselli and Sonderegger, 2025).

The interplay between enhanced mangrove conservation and agricultural expansion raises vital questions for future landscape management. The idea that development and conservation can coexist with careful planning is worth exploring (Cameron et al., 2019; Saoum and Sarkar, 2024). While balancing

ecological preservation and economic growth presents significant challenges, successful navigation can yield sustainable benefits for both local communities (Alongi, 2020; Cameron et al., 2019). Pongok Island illustrates this balance, showing gains in primary mangrove areas but declines in secondary forests, serving as both a success and a cautionary tale for long-term ecological stability.

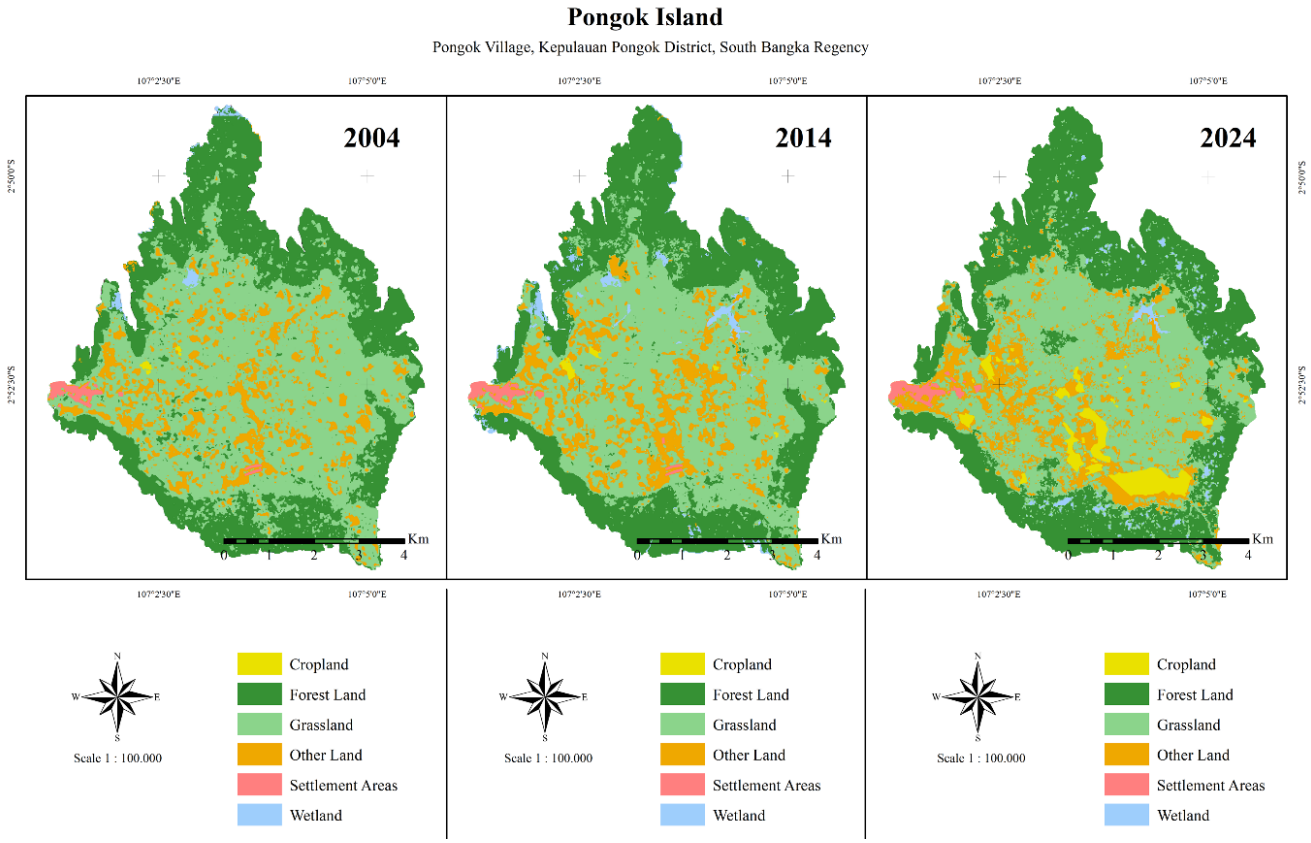

Figure 4. LULC changes in Pongok Island for the years 2004, 2014, and 2024

3.2 Biodiversity impacts and critical conservation thresholds

Landscape fragmentation analysis highlighted critical biodiversity thresholds (Tables 4 and 5). Kelapan Island experienced the most severe degradation, with a 29.5% decline in mean patch size and a 71.8% rise in edge density. Forest connectivity dropped to "very low" levels, indicating a high risk of species isolation. In contrast, Tinggi Island maintained a "medium-high" level of connectivity despite disturbances from mining. Pongok Island successfully preserved "high" connectivity while accommodating agricultural expansion.

Tinggi Island exhibits controlled fragmentation, with only three patches (7.1%) undergoing change over a two-decade period. This stability in patch numbers indicates that land-clearing is well-distributed, which is vital for species requiring moderate habitat. Research underscores the importance of patch stability for biodiversity conservation in fragmented landscapes (Fahrig, 2017; Yan et al., 2023). The observed decline of 6.5% in mean patch size suggests that, while fragmentation has occurred, it remains within manageable thresholds that most species can endure (Fahrig, 2017).

Furthermore, the 13.3% increase in edge density indicates a greater interface of habitat disturbance, which may subject species to ecological stress. According to the edge effects theory, conditions at habitat edges can significantly differ from those in the interior. These disparities may lead to heightened predation risk, fluctuations in humidity, and increased exposure to radiation (Reek et al., 2025). Importantly, while these changes are still within moderate ranges that can be addressed through targeted conservation efforts, the implications for species adapted to interior habitats must be carefully evaluated (Gaines et al., 2022).

Table 4. Major LULC changes by island (2004-2024)

Island	Change type	Area (ha)	Change (%)	Driver	Impact assessment
Tinggi	Forest regeneration	+18.26	+5.68	Natural succession, conservation	Positive conservation outcome
	Wetland expansion	+24.48	+7.74	Illegal tin mining activities, water-filled pits	Environmental degradation concern
	Cropland expansion	+7.28	+37.69	Agricultural intensification	Moderate agricultural pressure
	Secondary mangrove → Wetland	-4.48	-1.42	Natural tidal conversion + mining impacts	Mixed natural-anthropogenic process
Kelapan	Forest loss (net)	-38.1	-9.97	Land clearing for clove plantations and selective logging	Requires conservation intervention
	Secondary dryland → Grassland	-35.2	-19.05	Forest clearing for clove cultivation and grazing	Major habitat conversion
	Grassland expansion	+47.43	+12.31	Land clearing result, temporary grazing before clove planting	Landscape fragmentation
	Clove plantation development	+15.8	+22.16	New clove plantation establishment	Economic diversification
	Wetland dynamics	+2.31	+0.60	Variable tidal patterns	Coastal instability
Pongok	Forest regeneration (net)	+253.97	+5.38	Conservation efforts, natural recovery	Major conservation success
	Primary mangrove expansion	+275.76	+5.82	Restoration programs, protection efforts	Blue carbon enhancement
	Cropland expansion	+172.45	+3.59	Large-scale agricultural development, new rice fields	Major economic development
	Secondary mangrove → Wetland	-58.68	-1.22	Natural conversion + small-scale illegal tin mining (*kolong*)	Mixed natural-anthropogenic process
	Grassland → Forest conversion	+36.89	+1.49	Secondary succession, reforestation	Natural regeneration success
	Small-scale mining impacts	~5.20	~0.11	Illegal tin mining activities, localized kolong formation	Environmental monitoring needed

Table 5. Landscape fragmentation and biodiversity impact assessment

Island	Metric	2004	2014	2024	Change absolute	Change (%)	Biodiversity impact
Tinggi	Number of patches	42	48	45	+3	+7.1	Moderate fragmentation
	Mean patch size (ha)	7.52	6.59	7.03	-0.49	-6.5	Moderate habitat reduction
	Edge density (m/ha)	27.8	33.2	31.5	+3.7	+13.3	Mining-induced edge effects
	Shannon diversity index	1.32	1.45	1.48	+0.16	+12.1	Increased landscape diversity
	Forest connectivity	High	Medium	Medium-high	Recovery	-	Improving with regeneration
Kelapan	Number of patches	55	72	78	+23	+41.8	High fragmentation
	Mean patch size (ha)	6.99	5.34	4.93	-2.06	-29.5	Significant habitat loss
	Edge density (m/ha)	24.5	36.8	42.1	+17.6	+71.8	Severe edge effects
	Shannon diversity index	1.25	1.38	1.52	+0.27	+21.6	Diversity from fragmentation
	Forest connectivity	Medium	Low	Very low	Critical decline	-	High species isolation
Pongok	Number of patches	195	215	228	+33	+16.9	Controlled fragmentation
	Mean patch size (ha)	24.71	22.43	21.07	-3.64	-14.7	Manageable patch reduction
	Edge density (m/ha)	11.8	14.5	16.2	+4.4	+37.3	Moderate edge increase
	Shannon diversity index	1.18	1.32	1.41	+0.23	+19.5	Positive diversity increase
	Forest connectivity	High	High	High	Maintained	-	Conservation success

Kelapan Island displays concerning patterns of fragmentation that exceed critical conservation thresholds. The 41.8% increase in the number of patches indicates unplanned fragmentation resulting from land clearing, which undermines ecosystem integrity (Wintle et al., 2018). The 29.5% decline in mean patch size signals a serious warning regarding habitat degradation, as many species require specific

areas to thrive (Saravia et al., 2018). Furthermore, the 71.8% increase in edge density signifies a substantial structural change in the landscape, which may impact sensitive species, including large mammals and moisture-dependent amphibians (Fahrig, 2017).

Although the 21.6% rise in the Shannon diversity index may initially appear encouraging, it presents a paradox in which increased diversity correlates with fragmentation, thereby jeopardising the integrity of core habitats (Saravia et al., 2018). The marked decline in forest connectivity further restricts species movement, elevating their risk of extinction (Lindenmayer, 2023). These trends suggest that Kelapan Island's ecosystem may be approaching irreversible degradation without timely intervention (Saravia et al., 2018).

Pongok Island exemplifies notable conservation success by maintaining high levels of connectivity amid significant land-use changes. The moderate 16.9% increase in the number of patches (rising from 33 to 39) suggests a more structured form of fragmentation compared to Kelapan Island (Fahrig, 2017). Meanwhile, the 14.7% decline in mean patch size indicates a less severe impact, allowing for substantial habitat patches to remain intact. The 37.3% rise in edge density, while significant, is lower than that observed on Kelapan Island, reflecting more controlled landscape transformations (Timmers et al., 2025).

Furthermore, a 19.5% increase in the Shannon diversity index signifies adequate land-use diversification, balancing agricultural development with the preservation of connected forest areas. This high connectivity, bolstered by sound land management practices, enhances species movement and ecosystem resilience (Li et al., 2024). Consequently, Pongok Island's approach may exemplify land-sparing strategies by keeping agricultural and conservation areas distinct, thus preserving ecological integrity in the face of development pressures and serving as a model for tropical coastal regions (Lacambra et al., 2024).

3.3 Effectiveness of land-use management policies

Current regulations, including the Regulation of the Provincial Government of the Bangka Belitung Islands Province No. 3/2020, about the Zoning Plan for Coastal Areas and Small Islands, along with the Regulation of South Bangka Regency No. 6/2014, which outlines the Spatial Plan for South Bangka Regency. Regulatory gaps between marine and terrestrial governance frameworks have facilitated unregulated illegal mining and deforestation activities across all islands.

The regulatory failures across all three islands reveal a fundamental mismatch between governance structures and landscape-scale processes (Gunawan et al., 2024b; Setiawati et al., 2023). Marine-focused regulations inadequately address the drivers of terrestrial transformation, creating enforcement gaps that enable destructive activities (Tolessa et al., 2021; Dastour and Hassan, 2023). The upcoming Government Regulation No. 27/2025 on Mangrove Ecosystem Protection presents an opportunity to bridge these governance gaps through integrated coastal-terrestrial management frameworks (Mashala et al., 2023).

These findings have immediate implications for the hundreds of similar small islands across Indonesia and other archipelagic nations (Kelman, 2018; Révillion et al., 2019). The 20-hectare threshold and connectivity requirements provide concrete targets for conservation planning (Loos et al., 2015), while the Pongok Island model illustrates viable pathways for balancing development with ecosystem integrity (Reksa et al., 2021; Rimmer et al., 2021). The regulatory lessons emphasize the urgent need for governance frameworks aligned with the scale and complexity of small island socio-ecological systems (Lennert et al., 2020; Yetein et al., 2025).

Preserving biodiversity on small islands is crucial to maintaining habitat patch sizes of at least 20 hectares and ensuring high connectivity to prevent species isolation and local extinction. The conditions of the islands highlight this need: Kelapan has suffered significant degradation due to low connectivity, while Pongok demonstrates that mangrove expansion (approximately 275.76 hectares) can occur alongside agricultural growth with proper protection. The Provincial Government should lead in integrating land-sea governance by aligning spatial plans and coastal zoning, incorporating the "≥20 ha + connectivity" criterion into environmental licensing, and implementing effective monitoring and reporting systems to fill enforcement gaps.

4. CONCLUSION

This 20-year analysis of land use on small inhabited islands in South Bangka, Indonesia, reveals three transformation patterns influenced by human activities and natural processes. Tinggi Island shows forest resilience despite illegal tin mining, while

Kelapan Island faces severe ecological degradation and habitat fragmentation, prompting urgent conservation measures. In contrast, Pongok Island has successfully expanded its mangrove ecosystems despite the intensification of agriculture. A biodiversity impact assessment emphasizes the importance of maintaining patch sizes over 20 hectares and ensuring connectivity for species persistence. Current land-use management policies are ineffective due to a disconnect between marine and terrestrial governance, highlighting the need for integrated conservation strategies that balance development with ecosystem integrity. This research offers evidence-based recommendations for sustainable land-use planning and conservation.

ACKNOWLEDGEMENTS

The authors sincerely appreciate the financial support from the Indonesian Education Scholarship (BPI), Center for Higher Education Funding and Assessment (PPAPT), and Indonesian Endowment Fund for Education (LPDP), through Decree Number 00154/BPPT/BPI.06/9/2023, which enabled this doctoral study.

AUTHOR CONTRIBUTIONS

Henri conceptualised and methodologically carried out data collection and analysis, and drafted and revised the manuscript. Luchman Hakim, Catur Retnaningdyah, and Brian Rahardi contributed equally through supervision, critical review, and manuscript revision.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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